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THE EFFECT OF LAND MANAGEMENT ON CARBON AND NITROGEN STATUS IN PLANTS AND SOILS OF ALPINE MEADOWS ON THE TIBETAN PLATEAU

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ABSTRACT

Large-scale grassland rehabilitation has been carried out on the severely degraded lands of the Tibetan plateau. The grasslands created provide a useful model for evaluating the recovery of ecosystem properties. The purposes of this research were: (1) to examine the relative influence of various rehabilitation practices on carbon and nitrogen in plants and soils in early secondary succession; and (2) to evaluate the degree to which severely degraded grassland altered plant and soil properties relative to the non-disturbed native community. The results showed: (1) The aboveground tissue C and N content in the control were 105·97 g m^{-2} and 3·356 g m^{-2}, respectively. The aboveground tissue C content in the mixed seed treatment, the single seed treatment, the natural recovery treatment and the severely degraded treatment was 137 per cent, 98 per cent, 49 per cent and 38 per cent, respectively, of that in the control. The corresponding aboveground tissue N content was 109 per cent, 84 per cent, 60 per cent and 47 per cent, respectively, of that in the control. (2) Root C and N content in 0–20 cm depths of the control had an average 1606 g m^{-2} and 30·36 g m^{-2}, respectively. Root C and N content in the rehabilitation treatments were in the range of 26–36 per cent and 35–53 per cent, while those in the severely degraded treatment were only 17 per cent and 26 per cent of that in the control. (3) In the control the average soil C and N content at 0–20 cm was 11 307 g m^{-2} and 846 g m^{-2}, respectively. Soil C content in the uppermost 20 cm in the seeded treatments, the natural recovery treatment and the severely degraded treatment was 67 per cent, 73 per cent and 57 per cent, respectively, while soil N content in the uppermost 20 cm was 72 per cent, 82 per cent and 79 per cent, respectively, of that in the control.

The severely degraded land was a major C source. Restoring the severely degraded lands to perennial vegetation was an alternative approach to sequestering C in former degraded systems. N was a limiting factor in seeding grassland. It is necessary for sustainable utilization of seeding grassland to supply extra N fertilizer to the soil or to add legume species into the seed mix. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: alpine *Kobersia* meadow; carbon (C) and nitrogen (N) status; plants and soils; rehabilitation; severely degraded grasslands; Tibetan plateau

INTRODUCTION

The Tibetan plateau, the largest geomorphological unit on the Eurasian continent, is an important part of the global terrestrial ecosystem, and one of the world's major pasturelands. Grassland occupies an area of about 1·5 million km^2, and constitutes two-thirds of the total plateau area (Sun and Zheng, 1998). The main vegetation types of the Tibetan plateau are alpine cold meadow, steppe meadow and alpine cold steppe. Grasslands were generally thought to be inexhaustible for a long time. Their capacity to regenerate was often overestimated. In the 1950

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animal census, nearly 1·83 hm^2 of grassland was available for one adult sheep unit but the census of 1985 indicated that only 0·79 hm^2 of grassland was available per one adult sheep unit (Li and Zhou, 1998). Overgrazing has done massive harm to these grasslands (Li and Zhou, 1998). Besides overgrazing, the escalation of rodent populations (Liu and Wang, 1999; Li *et al.*, 1999), cryoturbation and climate change (warming) are major factors causing deterioration of plateau grassland (Ma, 1999). Under these extreme stresses, the exposed soil becomes susceptible to wind and water erosion. The evidence of grassland degradation is very notable on the Tibetan plateau. At present, 42·51 million hm^2 of degraded grasslands exist, occupying 33 per cent of the available grassland of the area. Severely degraded grassland accounts for an area of about 7·03 million hm^2, occupying 16·54 per cent of degraded grassland (Wang, 1997; Ma, 1999). The severely degraded grassland, also called 'black soil shale' by local people, is characterized by low forage production, low vegetation cover (0–40 per cent) and loss of the upper soil horizons (Ma, 1999). The investigation showed that the average aboveground biomass (wet) was about 400 kg hm^{-2} on severely degraded land in Dari County of Qinghai Province, which was only 13·23 per cent of the aboveground biomass for non-degraded native grassland, and the degraded vegetative cover was represented by less- and non-palatable species (Wang, 1997). The loss in forage production due to grassland degradation amounted to 103 million kg in Dari County, which was the annual forage requirement of about 70·6 thousand sheep (Wang, 1997). In order to cover the deficit in forage production and lessen pressure on natural grassland, it becomes essential to implement major rehabilitation strategies for severely degraded lands followed by proper management so that sustained forage production on a long-term basis can be achieved. Cultivars of native species were typically used in rehabilitation because of their performance, availability and price. Under the financial support of the Chinese Scientific-Technique Committee, large-area grassland rehabilitation has been carried out on severely degraded grasslands in Qinghai Province. During the period from 1998 to 2002, about 2000 hm^2 of seeding grasslands were established in the Guoluo Tibetan Prefecture of Qinghai Province.

At a global level, understanding how ecosystem carbon storage responds to changes in land degradation and land use will allow us to quantify the ecosystem feedbacks to these perturbations. The amount of carbon stored in terrestrial ecosystems (in the form of litter, living vegetation, and soil organic matter) is several times larger than the amount of carbon currently stored in the atmosphere as carbon dioxide (Schimel *et al.*, 1996). Thus, as terrestrial ecosystems change in response to human-induced environmental changes, there may be significant alterations in the atmospheric carbon dioxide content, which would constitute a feedback to climate. The Tibetan plateau is particularly sensitive to global climatic change (Cao *et al.*, 2004; Wang *et al.*, 2002). Moreover, the low temperature and consequent slow decomposition rates, which characterize these systems, can result in relatively large stocks of soil organic matter (Post *et al.*, 1982), which would obviously change in response to changing climatic conditions (Post *et al.*, 1982; Kirschbaum, 1995). On a regional scale, C and N are important elements in rangeland ecosystems. Soil organic matter is critical to the cycling of plant nutrients, influences water-retaining capacity and erosion potential, and is a key factor in soil structure (Tisdale and Oades, 1982). C and N budgets can serve as indicators of ecosystem health and sustainability (Wali, 1999).

The original ecosystem has been dramatically changed either by land degradation or by rehabilitation of severely degraded land. 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 storage in soils (Lal *et al.*, 1995). The extent to which soil and vegetation act as a CO_2 sink or source depends largely on land-use management. The alpine 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). However, it may also act as an important C source if land degradation or land use changes. Soil degradation and soil use change are therefore one of the critical factors controlling the C and N budgets for these ecosystems. Although land degradation/rehabilitation are widespread and sometimes large in scale, there is little information on the effect of land management on C and N storage in plants and soils in alpine meadows on the Tibetan plateau.

The objectives of this study were: (1) to examine the relative influence of various anthropogenic rehabilitation practices on C and N in plants and soils in early secondary succession; and (2) to evaluate the degree to which severely degraded grassland has altered vegetation and soil properties relative to non-disturbed native plant communities.

MATERIALS AND METHODS

Study Site and Experimental Design

We conducted this study in Dari County, Qinghai Province. The study site was located at latitude 32° 37′–34° 15′ N, longitude 98° 15′–100° 33′ E and at an altitude of 4090 m above sea level (Figure 1). The average annual precipitation from 1956 to 1997 was 536·6 mm, and 85 per cent of that rainfall was concentrated within the growing season from May to September. The average annual air temperature was −1·2°C, and the average air temperature was 9·1°C in July, −12·9°C in January (The Livestock Husbandry Programming Office of Qinghai Province, 1987). Native vegetation was mainly alpine *Kobersia* meadow, which was dominated by *Kobersia pygmaea*, *Elymus nutans* and the most common species included *Festuca ovina*, *Poa* sp., *Carex pachyrrhiza*, and *Thalictrum alpinum* var. *elatum* (Zhou *et al.*, 1987). The soil of the study site (no land degradation) was classified as alpine meadow soil (Mat Cry-gelic Cambisols) derived from granitic drift. The soil surface was well developed with a mixture of root mass and clay to a depth of about 5–10 cm. It was quite hard and resilient due to a thick and dense sod layer. Alpine meadow soils are usually coarse textured and stony, and belong to sandy-loam soil. The severely degraded grassland was dominated by *Descurainia sophia*, *Pedicularis kansuensis*, *Ajuga lupulina* and *Polygonum sibiricum*. The total vegetation cover was less than 40 per cent. The soil of degraded land was classified as erosion alpine meadow soil, which belongs to medium loam lithosoil (The Agriculture Programming Office of Qinghai Province, 1997).

The rehabilitation of severely degraded land began in the spring of 1998. In this study, we chose five treatments: (1) a non-disturbed native alpine *Kobersia* meadow as control (CK); (2) a mixed *Elymus sibiricus/Poa crymophila* (2:1) seed treatment (MS); (3) a single *E. sibiricus* seed treatment (SS); (4) a non-seeded natural recovery treatment (NR); and (5) a severely degraded treatment (D). There were three rehabilitation measures, namely two seeded treatments and a natural recovery treatment. Three plots were established for each treatment. The plots with different treatments were located as closely as possible to each other, in places with comparable topography, soil and vegetation types (which appeared to be present before degradation).

Rehabilitation measures at the two seeded treatments were organized as follows: severely degraded lands were plowed, harrowed, and perennial grasses planted, then again harrowed lightly and trampled to prevent soil erosion.

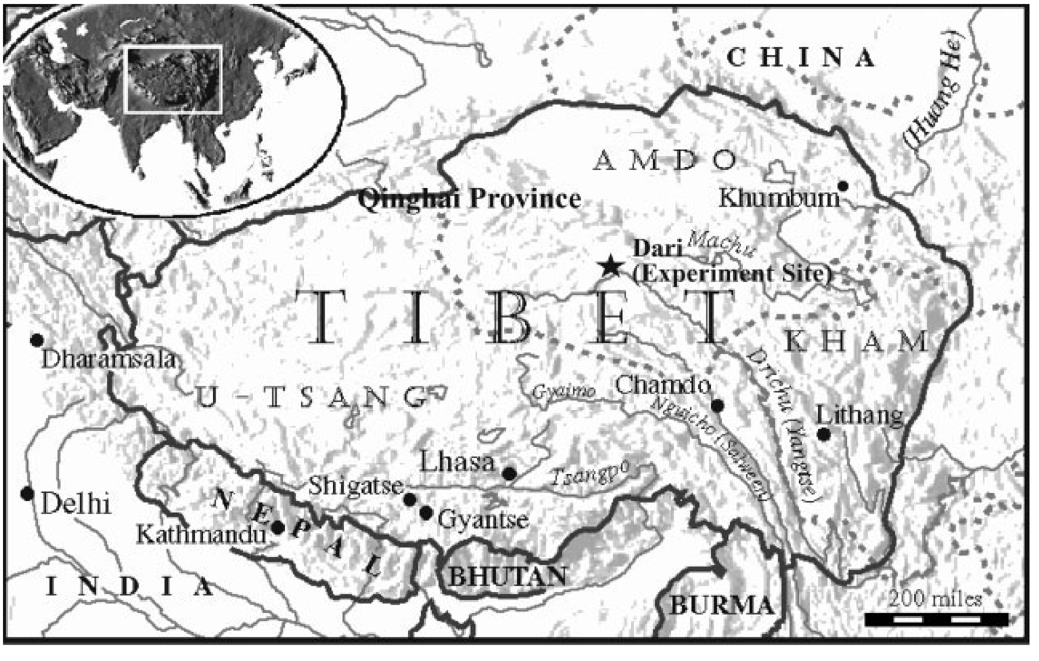

Figure 1. Location of the experimental site on the Tibetan plateau.

Seeds were hand broadcast at a depth of 2–3 cm, the seeding rate varied from 20–23 kg hm^{-2}. Seeding was completed on 15 June 1998. In seeding plots at least two weedings may be carried out in the first year of establishment. Undesirable non-palatable weeds were removed. Reseeded grasslands should not be grazed in the first year of establishment, but grazing may be permitted in winter starting in the second year of establishment. The natural recovery treatment was that severely degraded lands have been fenced to exclude grazing by sheep and yaks since 1998. The difference between the natural recovery treatment and the severely degraded treatment was that the former was fenced to avoid disturbance, and the latter was not fenced.

Three plots per treatment (10 m × 10 m) were established for measurements. All samples were collected on August 2003.

Vegetation

Total vegetation ground cover was measured in all plots. At each plot, percentage cover of each plant species was recorded and vegetation was clipped off flush with the ground from five 0·25 m^2 quadrats. The harvested plants were separated into grasses, sedges and forbs. The dominant species was selected according to its relative percentage cover on the plot. Root biomass was sampled in 10 soil cores (diameter 5 cm) per plot at 0–20 cm depths. The soil cores were placed in polyethylene bags and stored at 4°C. In the laboratory, samples were crumbled by hand to pass through a 4 mm diameter sieve to separate large root segments from the soil. Large root fragments and the associated soil were then washed over a 0·25 mm sieve to retrieve fine roots. No attempt was made to distinguish between live and dead roots. All vegetation material was oven dried (48 h, 70°C) and weighed. Vegetation samples ground in an agate mortar were analyzed for total carbon and nitrogen concentration by dry combustion in a VarioEL® elemental analyzer.

Soil

Soils were collected from all plots. At each plot, 10 soil cores (3·5 cm diameter) were collected from random locations and separated into 0–10 cm and 10–20 cm depths. Samples were composite by plot and depth in the field. The air-dried soil samples were passed through a 2 mm sieve to remove the coarse fraction (gravel and roots), and then weighed. The dry mass of the sieved soil (< 2 mm) was calculated by subtracting the weight of the coarse fraction from the total soil dry mass. Percentage coarse fraction (gravel relative mass) was calculated as: $100 \times [(\text{dry mass} > 2\,\text{mm})/((\text{dry mass} < 2\,\text{mm}) + (\text{dry mass} > 2\,\text{mm}))]$. Bulk density was sampled from 0–10 and 10–20 cm depths using rings of 5·3 cm in diameter. It was calculated from the total weight of the known volume. Soil samples ground in an agate mortar were analyzed for total organic carbon (TOC) concentration, total nitrogen (TN) 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.

Soil total organic C (or total N) content (kg m^{-2}) $= D \times B \times C \times ((100–S)/100)$, where D is the soil depth, B the soil bulk density, C the soil organic carbon (or total nitrogen) concentration in the sieved (< 2 mm) soil fraction and S the percentage of the coarse fraction (> 2 mm) in the sample, i.e. gravel was excluded from analyses. SPSS® software was used to test for significant differences among treatments using least significant difference techniques.

RESULTS

Plant Community Characteristics

The control treatment contained about 36 species, which provided 95 per cent total ground cover, and was dominated by *K. pygmaea*, *E. nutans*, *Poa* sp., and *T. alpinum* var. *elatum*. The mixed seed treatment, with 90 per cent total ground cover, contained 27 species and was dominated by *E. sibiricus* and *P. crymophila*. The single seed treatment, with 74 per cent total ground cover, contained 23 species and was dominated by *E. sibiricus*

Table I. Mean (± standard error) grasses, forbs and sedges biomass under different treatments

Treatment	Grasses (g m^{-2})	Forbs (g m^{-2})	Sedges (g m^{-2})
CK	152·27 (31·96) b	49·35 (2·08) cd	54·93 (6·40) a
MS	348·13 (24·19) a	8·83 (6·57) d	—
SS	181·39 (45·23) b	69·03 (15·76) bc	—
NR	1·13 (0·47) c	140·23 (15·60) a	0·07 (0·07) b
D	1·49 (0·11) c	96·40 (17·89) b	—

Note: Treatment means for a variable were not significantly different (ANOVA, $\alpha = 0{\cdot}05$) if followed by the same letter.
CK: control; MS: mixed seed; SS: single seed; NR: natural recovery; D: severely degraded land.

and *Pedicularis kansuensis*. The natural recovery treatment contained 22 species, provided 63 per cent total ground cover and was dominated by *Potentilla anserina* and *P. sibiricum*. The severely degraded treatment contained 16 species, had only 38 per cent total ground cover, and was dominated by *D. sophia*, *Pleurospermum candollei* and *Lagotis glauca*.

Aboveground Biomass Under Different Treatments

Grasses dominated aboveground biomass in the seeded treatments after six growing seasons. Forbs in the natural recovery treatment and severely degraded treatment dominated aboveground biomass production (Table I).

Table I shows that grass biomass in the control was significantly lower than that in the mixed seed treatment. On the other hand, it was significantly higher than that in the natural recovery treatment and the severely degraded treatment, between which there were no significant differences. Forb biomass decreased from the natural recovery treatment, to the severely degraded treatment, to single seed treatment, to the control, to mixed seed treatment. Forb biomass was significantly higher in the natural recovery treatment than in the severely degraded treatment. This suggested that a lot of forbs as pioneer species had invaded, and established during the natural recovery. In addition, there was much more forb biomass in the single seed treatment than in the mixed seed treatment. Sedges only appeared in the control treatment and as a small contribution in the natural recovery treatment.

Plant Aboveground Tissue C and N Under Different Treatments

Few significant differences in aboveground tissue C concentration for grasses and C, N concentration or C:N ratio for forbs and sedges were observed among all treatments (Table II). Grass N concentration was significantly lower in the seeded treatments than in the natural recovery and the severely degraded treatments. Thus grass C:N ratio was significantly higher for the seeded treatments. In addition, N concentration was higher in forbs (average 1·42 per cent) than in grasses (average 1·23 per cent) (Table II).

Table II. C, N concentration (%) and C:N ratio of grasses, forbs and sedges under different treatments

Treatment	Grasses			Forbs			Sedges		
	C (%)	N (%)	C:N	C (%)	N (%)	C:N	C (%)	N (%)	C:N
CK	40·48	1·27ab	31·92ab	43·93	1·53	28·75	41·47	1·22	34·00
MS	40·55	1·02b	39·91a	41·13	1·40	29·44	—	—	—
SS	41·47	1·09b	38·05a	40·83	1·23	33·33	—	—	—
NR	35·48	1·36a	26·09b	36·64	1·41	25·94	40·25	1·18	34·11
D	38·69	1·49a	25·93b	40·79	1·60	25·53	—	—	—

Note: Treatment means for a variable were not significantly different (ANOVA, $\alpha = 0{\cdot}05$) if followed by the same letter. Absence of letter indicates that no significant difference was found.
CK: control; MS: mixed seed; SS: single seed; NR: natural recovery; D: severely degraded land.

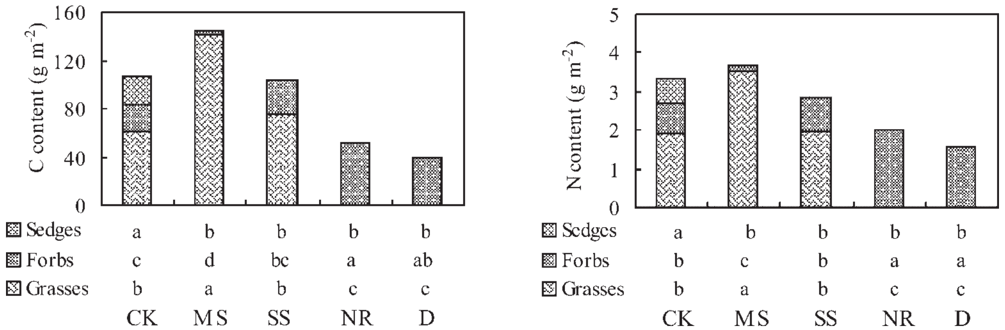

Figure 2. Aboveground C and N content (g m^{-2}) for grasses, forbs and sedges under different treatments. *Note*: Means for a variable (grasses, forbs or sedges) were not significantly different among treatments (ANOVA, $\alpha = 0{\cdot}05$) if followed by the same letter. CK: control; MS: mixed seed treatment; SS: single seed treatment; NR: natural recovery treatment; D: severely degraded land.

Grass C and N content followed the same patterns as grass biomass (Figure 2). Forb C and N contents in the control were significantly lower than those in the natural recovery treatment and the severely degraded treatment, and were higher than in the mixed seed treatment. Sedge C and N content were significantly higher in the control than in other treatments.

The total aboveground tissue C and N contents in the control were 105·97 g m^{-2} and 3·356 g m^{-2}, respectively (Figure 2). The total aboveground tissue C content in the mixed seed treatment, the single seed treatment, the natural recovery treatment and the severely degraded treatment was 137 per cent, 98 per cent, 49 per cent and 38 per cent, respectively, of that in the control. The corresponding total aboveground tissue N content was 109 per cent, 84 per cent, 60 per cent and 47 per cent, respectively, of that in the control.

Root Biomass and Root Tissue C and N Under Different Treatments

The root biomass in the uppermost 20 cm of the control had an average value of 4958 g m^{-2}. It was significantly higher than that of all rehabilitation treatments, among which there were no statistically significant differences (Table III). The root biomass was significantly higher in the mixed seed treatment than in the severely degraded treatment. No statistically significant differences in root C concentration were measured among all treatments. The N concentration in root tissue was significantly lower in the control than in the other treatments, among which there were no significant differences. Thus root C:N ratio was significantly higher for the control. As expected, C content in roots followed the same pattern as root biomass. The root N content was significantly higher in the control with large root biomass than in other treatments and higher in the natural recovery treatment and the mixed seed treatment than the severely degraded treatment. In short, root biomass, root C and N content were higher in the control than in all rehabilitation treatments, among which there were no significantly differences. Root C and N content were larger for all rehabilitation treatments than for the severely degraded treatment.

Table III. Mean (± standard error) root biomass and root tissue C and N under different treatments

Treatment	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})
CK	4958 (820) a	32·37 (1·41)	0·620 (0·050) b	52·5 (4·4) a	1606 (272) a	30·36 (2·65) a
MS	1556 (150) b	36·94 (0·94)	1·023 (0·071) a	36·5 (3·0) b	581 (75) b	15·97 (1·98) b
SS	1141 (97) bc	37·20 (0·59)	0·952 (0·093) a	39·7 (3·4) b	424 (30) bc	10·70 (0·42) bc
NR	1328 (182) bc	36·99 (0·37)	1·202 (0·083) a	31·1 (2·4) b	490 (62) bc	16·22 (3·34) b
D	730 (77) c	36·72 (1·76)	1·073 (0·086) a	34·7 (3·3) b	270 (36) c	7·75 (0·63) c

Note: Treatment means for a variable were not significantly different (ANOVA, $\alpha = 0{\cdot}05$) if followed by the same letter. Absence of letter indicates that no significant difference was found.
CK: control; MS: mixed seed; SS: single seed; NR: natural recovery; D: severely degraded land.

Root C and N content of the control had averages of 1606 g m^{-2} and 30·36 g m^{-2}, respectively. Root C and N content in the rehabilitation treatments were in the range of 26–36 per cent and 35–53 per cent, respectively, of that in the control after six growing seasons. C and N content in roots of the severely degraded treatment were only 17 per cent and 26 per cent, respectively, of that in the control. So, in the severely degraded land, the losses of C and N content in roots were 1336 g m^{-2} and 22·61 g m^{-2}, respectively, with destruction of the dense sod layer.

Soil C Concentration, N Concentration, Bulk Density, and Gravel Relative Mass for the 0–10 and 10–20 cm Depths Under Different Treatments

Soil C concentration in the uppermost 10 cm was significantly higher in the control than in the other treatments. It was significantly higher in the natural recovery treatment than the severely degraded treatment (Table IV). Although there were no significant differences for soil C concentration in the uppermost 10 cm among the rehabilitation treatments, it was numerically higher in the natural recovery treatment than in the seeded treatments. The pattern of soil C concentration in the 10–20 cm depth was in essence the same as that in the 0–10 cm depth.

Soil N concentration in the control was significantly higher than that in other treatments in both 0–10 and 10–20 cm depths (Table IV). In addition, soil N concentration in the natural recovery treatment and the severely degraded treatment was larger than that in the seeded treatments in both 0–10 and 10–20 cm depths.

Bulk density in 0–10 cm depth was significantly lower in the control than in the rehabilitation treatments, among which it did not differ significantly (Table IV). It was higher in all rehabilitation treatments than in the severely degraded treatment. Bulk density of the subsurface soil layer had the same pattern as that of the first 10 cm.

Gravel relative mass in the 0–10 cm depth soil was significantly lower in the control than other treatment, among which there were no significant differences (Table IV). In the 10–20 cm depth soil, it was significantly lower in the control than in the natural recovery treatment and the severely degraded treatment. This suggested that land degradation leads to more coarse-textured and stonier alpine soils.

Soil C and N Content for 0–10 and 10–20 cm Depths Under Different Treatments

The result for the three variables (concentration, bulk density and gravel relative mass) measured to estimate soil C or N content is shown in Figure 3. Soil C content followed the same pattern as soil C concentration in both 0–10 cm and 10–20 cm depths (Figure 3). Soil N content had virtually the same pattern as soil N concentration except the N content in the subsurface, where no significant differences occurred among seeded treatments, the natural recovery treatment and the severely degraded treatment.

In the top 20 cm, soil C and N content were highest in the control treatment, which resulted from high soil C, N concentration and low gravel mass. The average soil C and N content were 11 307 g m^{-2} and 846 g m^{-2} respectively in the control in the 0–20 cm depths (Figure 3). Soil C content in the uppermost 20 cm in the seeded treatments, the natural recovery treatment and the severely degraded treatment was 67 per cent, 73 per cent and 57 per cent, respectively, of that in the control, while soil N content in the uppermost 20 cm was 72 per cent, 82 per cent and 79 per cent, respectively. Lost soil C and N content were 4863 g m^{-2} and 175 g m^{-2}, respectively, in

Table IV. Mean ($\pm$ standard error) soil total organic C, N concentration, bulk density, and gravel relative mass for the 0–10 and 10–20 cm depths under different treatments

Treatment	C concentration (%)		N concentration (%)		Bulk density (g cm^{-3})		Gravel relative mass (%)	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
CK	7·18 (0·42) a	6·70 (0·29) a	0·542 (0·045) a	0·497 (0·020) a	0·90 (0·07) c	1·13 (0·06) c	14·0 (1·7) b	24·0 (2·1) b
MS	4·16 (0·20) bc	4·22 (0·23) b	0·319 (0·016) c	0·345 (0·017) bc	1·22 (0·02) b	1·32 (0·02) b	30·3 (2·0) a	31·0 (1·5) ab
SS	4·66 (0·21) bc	3·87 (0·18) b	0·366 (0·022) bc	0·326 (0·021) c	1·24 (0·07) b	1·40 (0·06) b	30·0 (1·5) a	31·7 (1·8) ab
NR	4·99 (0·33) b	4·45 (0·19) b	0·413 (0·019) b	0·387 (0·019) b	1·24 (0·03) b	1·34 (0·04) b	29·0 (2·7) a	34·7 (3·4) a
D	4·10 (0·16) c	2·93 (0·15) c	0·388 (0·026) bc	0·363 (0·015) bc	1·43 (0·04) a	1·47 (0·03) a	36·3 (3·7) a	38·7 (3·3) a

Note: Treatment means for a variable were not significantly different (ANOVA, $\alpha = 0{\cdot}05$) if followed by the same letter.
CK: control; MS: mixed seed; SS: single seed; NR: natural recovery; D: severely degraded land.

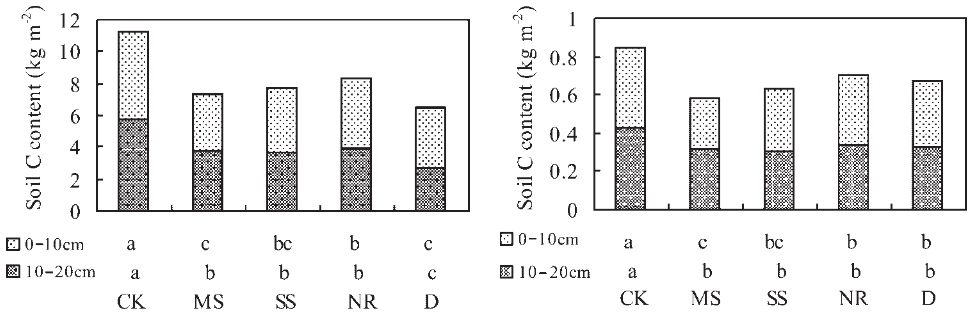

Figure 3. Soil total organic C and total N content (kg m^{-2}) for 0–10 cm and 10–20 cm depths under different treatments. *Note*: Means for a variable (0–10 cm depth or 10–20 cm depth) were not significantly different among treatments (ANOVA, $\alpha = 0{\cdot}05$) if followed by the same letter. CK: control; MS: mixed seed treatment; SS: single seed treatment; NR: natural recovery treatment; D: severely degraded land.

20 cm depths in the severely degraded land. This suggested that there were a lot of soil C and N losses in severely degraded land. The loss of soil C was more significant than that of soil N in the severely degraded treatment.

DISCUSSION

Vegetation Changes Under Different Treatments

The native alpine *Kobersia* meadow is characterized by the dominance of *Kobersia* plants that are perennial geophyta rhizomatosa (Zhou and Li, 2001). Reproduction of *Kobresia* plants such as *Kobersia pygmaea* and *K. humilis* in an alpine environment are mainly by clone. *Kobersia* plants may produce mature seeds, but the germination rate of these seeds was nearly zero in the field experiments (Deng and Zhou, 2001). Therefore, cultivars of native grasses with high germination rate such as *E. sibiricus*, *P. crymophila* and *E. nutans* were usually used to rehabilitate severely degraded lands on the Tibetan plateau.

Plant productivity is an important metric of ecosystem functioning for alpine meadows. In the sixth year of rehabilitation, the total aboveground biomass and ground cover of all rehabilitation treatments were higher than those in severely degraded land. This suggests that the rehabilitation measures may promote aboveground biomass, particularly grass biomass in seeded treatments, and ground cover. This is important for the region to supply winter forage and to decrease the pressure on native grassland. Establishment of grasses in the natural recovery treatment progressed slowly compared to that of the seeded treatments. From this perspective, seeding accelerates succession. The mixed seed treatment resulted in a significantly higher grass biomass and lower forb biomass compared to the single seed treatment (Table I). This suggests that mixed seed treatment may have inhibited the establishment of forbs, while single seed treatment may give chance to the establishment of annual forbs (*P. kansuensis*). The reason may be that *E. sibiricus* is a tall-grass and *P. crymophila* is a short-grass. They occupied different spatial positions and thus inhibit the establishment of exotic species. The assemblage of differential species (different performance potential) is an important factor determining potential community composition and succession (Hammermeister, 2001). In our study, mixed grassland is more stable in community structure than single seeding grassland.

The root biomass of the alpine *Kobersia* meadow varies with plant community composition. Root biomass in the uppermost 40 cm in September are $11{\cdot}18$ kg m^{-2}, $5{\cdot}61$ kg m^{-2} and $2{\cdot}43$ kg m^{-2} in *Kobersia tibetica* meadow, *K. pygmaea* meadow and *K. humilis* meadow, respectively, at Haibei station (Wang, 2001). Although native alpine *Kobersia* meadow (except *K. tibetica* meadow) roots can extend to about 40–50 cm deep into the soil, 75–90 per cent of this biomass resides in the surface 0–10 cm (Wang, 2001). More biomass is allocated belowground than aboveground in the native *Kobersia* meadows. Root input represents the primary sources of organic matter input into the soil environment (Cao and Zhang, 2001). No significant differences in root biomass occurred among the natural recovery treatment and seeded treatments. Root biomass in rehabilitation treatments is 23–31 per cent of that in the control. The root biomass in the severely degraded treatment was 14·7 per cent of root biomass in the control. So, one of the main features of the severely degraded land was the loss of the originally dense sod layer in the native *Kobersia* meadow. The rehabilitation may in part have recovered belowground biomass in six growing seasons. According to the results of Hammermeister (2001), root biomass of natural recovery and seeded rehabilitation following wellsite disturbance reached approximately 30 per cent and 50 per cent of root biomass of the non-disturbed native grassland (prairie), respectively, in three growing seasons in southeastern Alberta, Canada. This was partly attributed to the larger belowground biomass in the native *Kobersia* meadow than in the native prairie of Alberta.

Nutrient supply to the plant actually depends on the mobility of ions and root density (Lavelle and Spain, 2001). The depletion of poorly mobile ions (e.g. NH_4^+, $H_2PO_4^-$) in roots rose linearly with increase of root density (Lavelle and Spain, 2001). In the native *Kobersia* meadow with large root density and low biological nitrogen fixation (Cao and Zhang, 2001), available N in the soil is mainly represented by NH_4^+–N (Cao and Zhang, 2001), which is a poorly mobile ion in a soil. So these may be one reason for the low N concentration in the roots of the control. In addition, a lot of dead roots with low N concentration (Li and Zhou, 1998) were reserved in the soil of native *Kobersia* meadow (Wang, 2001). This is another reason for the low N concentration in roots of the control.

The rehabilitation treatments exhibited a relatively low quantity of high-quality root biomass (as index by C:N ratio) while the native *Kobersia* meadow contained a greater quantity of lower quality (high C:N ratio) root mass, which results in a storage of large amounts of slowly decomposing C belowground. Along with the factors of low soil temperature and weak microbial activity (Zhou and Li, 2001), this may be one of the reasons why a large amount of roots were stored belowground in native *Kobersia* meadow.

Soil Chemical Change Under Different Treatments

The alpine meadow on the Tibetan Plateau has the highest soil organic carbon density of all sino-Tibetan terrestrial areas (Wang and Zhou, 1999). Organic carbon storage in the grassland soils on the Tibetan Plateau accounts for 2·5 per cent of the global soil carbon pool. The soil C pool of the Tibetan Plateau is of great importance globally (Wang *et al.*, 2002). Nitrogen limitation is a key characteristic of the alpine meadow ecosystem. Although alpine meadow soils are noted for their large quantities of total N, most of this N resides in organic (unavailable) form. Inorganic (available) N is usually present in low concentrations (Cao and Zhang, 2001).

Soil C and N content in the uppermost 20 cm in the severely degraded treatment were 43 per cent and 21 per cent lower than that in the control, respectively. Guo and Gifford (2002) reviewed the literature for the influence of land use changes on soil C stocks and report the results of a meta-analysis of these data from 74 publications. The result indicates that soil C stocks decline after land use changes from pasture to plantation (−10 per cent), native forest to plantation (−13 per cent), native forest to crop (−42 per cent), and pasture to crop (−59 per cent). This suggests that the loss of C stock in alpine meadow soil due to land degradation would roughly equate to the loss of C stock of land use change from forest to crop. Grieve (2000) studied the effects of human disturbance and cryoturbation on soil organic matter storage at high elevations in the Cairngorm Mountains, Scotland, and showed that trampling was principally associated with a loss of the surface soil horizons and cryoturbation processes with disturbance of horizon development. The median total C storage of the vegetated soils was 6·5 kg m^{-2}, more than twice the median of 3·0 kg m^{-2} of the disturbed (unvegetated) soil. The loss of soil C here (54 per cent) was more than that in our study (43 per cent). Compare with loss of C amount, loss of N amount in the uppermost 20 cm soil was less in the severely degraded land. The difficulty of identifying the main causes of soil nitrogen loss was pointed out by Ghadiri and Rose (1991). They considered that nitrogen loss, even if largely in organic forms, does not have to exactly follow the loss of organic matter. Martinez-Mena (2002) studied soil organic C and N changes in a non-disturbed system with natural vegetation and a disturbed system (vegetation removal). It was shown that nine years after vegetation removal, significant differences were found in the soil organic carbon content between the systems (top 20 cm), but not in soil total nitrogen.

Compared with the natural recovery treatment, there is lower C and N content in the uppermost 20 cm of soil in the seeded treatments. The decline was primarily attributed to soil disturbances during seeding. In addition, since the seeded grasslands were grazed in winter, there may be a decrease of organic matter input to the soil. Soil C content in the top 20 cm was larger in all rehabilitation treatments, especially in natural recovery treatment, than in the severely degraded treatment. The recovery of soil C may primarily be attributed to increased C inputs in the rehabilitation treatments. So, restoring the severely degraded lands to perennial vegetation is an alternative approach to sequestering C in former degraded system. The establishment of perennial grasses or natural recovery can promote the recovery of soil C pools. However, soil N content down to 20 cm depth was higher in the natural recovery treatment and the severely degraded treatment than in the seeded treatments. This suggested that there was more soil N loss under seeded treatments. Fertilization experiments in *E. sibiricus* man-made grassland were carried out on the Haibei Station of the Chinese Academy of Sciences. The result showed that extra N fertilizer may improve nutrient supply from soil to plant, promote growth of plants and maintain stable and sustainable grassland productivity (Zhao and Zhang, 2001). So we considered that N (especially available N) is a limiting factor in seeding grassland. It is necessary for sustainable utilization of seeding grassland to supply extra N fertilizer to the soil or to add legume species to the seed mix.

In our study, residual effects of land degradation on soil physical and chemical properties of rehabilitation grasslands are evident from comparisons with the native *Kobersia* meadow. But, compared with the unrestored state, grassland rehabilitation or recovery may increase above/belowground biomass, and in part improve soil physical and chemical properties. In most cases complete restoration may not be feasible, and rehabilitation or recovery may be more appropriate options if the endpoint would still be more valuable than the unrestored state (Baer, 2001).

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