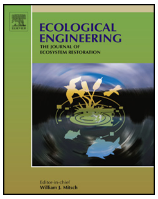
Ecological Engineering 71 (2014) 133–143

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Comparison of ecosystem characteristics between degraded and intact alpine meadow in the Qinghai-Tibetan Plateau, China

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ARTICLE INFO

Article history:
Received 26 February 2014
Received in revised form 22 May 2014
Accepted 12 July 2014

Keywords:
Alpine meadow
Degradation
Plant
Soil
Qinghai-Tibetan Plateau

ABSTRACT

Climate warming and overgrazing are inducing degradation of the alpine meadow ecosystem on the Qinghai-Tibetan Plateau. The Plateau is an important pastoral region in China and controversy surrounds the estimated carbon release occurring in this region of the world. Nevertheless, little comprehensive research analyzing land degradation has been conducted involving multiple factors in this region. Using two years of observational data, we compared differences in air temperature and relative humidity, soil temperature and moisture, soil texture, soil bulk density, soil organic carbon, soil respiration, vegetation height, coverage and biodiversity, above- and below ground biomass between moderately degraded and intact alpine meadow, and analyzed their relationships. The results show that the main process occurring during degradation was that *Spenceria* species and weeds with deep roots and a relatively high ability to resist drought replaced *Kobresia* species that previously exhibited high vegetation coverage and low vegetation height in alpine meadows of the Qinghai-Tibetan Plateau; these changes fundamentally affected corresponding changes in soil physical, chemical and thermal characteristics of the meadows. The change of vegetation species is believed to be the result of drought in the shallow soil of this habitat and is controlled by temperature and precipitation. The results suggest that a good collocation between temperature and precipitation is beneficial to the development of the alpine meadows; conversely, a poor pairing of temperature and precipitation not only causes the degradation of alpine meadows, it can even continually intensify the process by creating a vicious circle involving changes in soil physical, chemical, thermal and hydraulic conditions.

1. Introduction

Land degradation caused by climate change and human activities has attracted extensive attention worldwide, especially in arid regions, because the reduced land productivity combined with the increasing human population result in poverty and famine; these conditions severely impede efforts to achieve sustainable development targets in the future (UNCCD, 1994, 2008; UNCSD, 2012). Land degradation occurs not only in arid and semi-arid regions, it occurs on the Qinghai-Tibetan Plateau at high elevations and in alpine climates in past 20 years (Yang et al., 2004; Xue et al., 2009; Harris, 2010; Wang et al., 2012; Zeng et al., 2013). Many types of evidence have proven that climate warming causes degradation of permafrost, the active layer, glaciers, lakes, and marshes (Cheng et al., 1993; Zhao et al., 2004; Pu et al., 2007; Wu and Zhang, 2008; Wu and Zhang, 2010; Yang et al., 2010; Cheng and Wu, 2007); these changes accordingly result in the degradation of alpine ecosystems by causing drought near the soil surface, the loss of soil organic matter, the release of soil carbon and nitrogen, a decrease of biomass, reduced biodiversity, and an increase in wind erosion, etc. (Wang et al., 2007a, 2011, 2012; Xue et al., 2009; Wen et al., 2010; Zeng et al., 2013). Some researchers have also pointed out that overgrazing can cause or intensify the degradation of alpine ecosystems by destroying vegetation coverage (Du, 2004; Shang and Long, 2005; Song et al., 2009), but climate warming is thought to be the main cause of land degradation in the Qinghai-Tibetan Plateau (Klein et al., 2007; Xue et al., 2009; Harris, 2010; Zeng et al., 2013).

The Qinghai-Tibetan Plateau is called “the third pole” because the mean elevation stands 4000 m above sea level and it covers

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http://dx.doi.org/10.1016/j.ecoleng.2014.07.022
0925-8574/

an area of 2.0 × 10^6 km^2 (Harris, 2010; Cheng and Wu, 2007). The processes involved in the degradation of the alpine ecosystem in the Qinghai-Tibetan Plateau are very different from those in arid regions due to its uniquely cold environment and humid characteristics. The interaction of heat and water fluxes and their impact on the ecosystem may play important roles in the process of degradation (Wang et al., 2008; Hu et al., 2009). Few studies have been conducted in the Qinghai-Tibetan Plateau that were designed to understand the influence of the degraded alpine ecosystem on soil temperature, soil moisture, vegetation, soil nutrients or soil respiration (Cao et al., 2004; Klein et al., 2004; Yang et al., 2004; Wang et al., 2007b, 2012; Hu et al., 2009; Zeng et al., 2013). A comprehensive exploration involving a variety of environmental factors has not been conducted in the Qinghai-Tibetan Plateau. Those factors might include soil temperature, moisture, and texture, as well as soil organic matter and respiration. In addition, such a study might include the coverage, height, biomass and diversity of plants as well as the microclimate near the surface. It is also important to understand the cause and processes of land degradation in alpine ecosystems, and to forecast the changes occurring in alpine ecosystems with a warming climate and increasing human population.

Alpine meadows cover an area of 4800 × 10^4 ha in regions with elevations over 4200 m above sea level in the southern and eastern parts of the Qinghai-Tibetan Plateau and include 38% of all grassland area in the Plateau (DAHVGS and GSAHV, 1996). The annual average temperature in the alpine meadows is lower than 0 °C, but solar radiation can reach 670–837 kJ/cm^2 because these high elevation sites receive intense sunshine (DAHVGS and GSAHV, 1996). High temperatures during the day benefit photosynthesis of these forage plants while low temperature at night weakens their respiration rate and is still beneficial to the accumulation of aboveground biomass; therefore, alpine meadows serve as the main pasture grassland in the Plateau.

The high elevation and low temperatures make the alpine meadow ecosystem sensitive to climate warming, and hence easily degraded. However, recovering their ecological structure and biodiversity similar to that of the original conditions will require 45–60 years after alpine meadows become degraded (Jin et al., 2008). Degradation of alpine meadows can directly affect the carrying capacity of pastures and the livelihood of local people; this type of degradation is also presumed to indirectly affect regional climate, because alpine meadows store more soil organic carbon than alpine steppes (Yang et al., 2009a). A positive feedback may be present and increasing regional air temperatures as a result of the increasing release of carbon from degraded meadows (Wang et al., 2002; Xu et al., 2004; Schaefer et al., 2011).

Therefore, we selected moderately degraded alpine meadow (MDAM) and intact alpine meadow (IAM) as the research objects in an attempt to reveal the degradation mechanism of alpine meadow habitat and to understand how degraded alpine meadow develops and how MDAM affects the biogeochemical cycle, by comparing the differences in soil, plant and microclimate characteristics of MDAM and IAM.

2. Materials and methods

2.1. Site description

The processes of weathering and the development of soil in alpine meadows of the Qinghai-Tibetan Plateau occur very slowly because of the high elevation and cold climate. Therefore, the soil layer with abundant organic matter averages only 30 cm thick, although it can reach 50 cm in some regions. Under the soil layer, coarse particles make up the largest percentage of substrate, which results in rapid water conductivity and weak water holding capacity. In the surface layer of soil, dense, compact and flexible roots compose the 0–10 cm turf layer, which can protect fine soil particles from wind and water erosion. However, the yearly and daily process of freeze/thaw in soil can lead a loss of the turf layer, especially in some regions with steep slopes. Without the protecting turf, fine particles in the surface layer are easily eroded by the strong winds predominant in the Qinghai-Tibetan Plateau; then the underlying coarse particles become exposed and alpine meadow is replaced by the bare land covered by sand and gravel. Climate warming and overgrazing can exacerbate the soil freeze/thaw process, and this accelerates land degradation.

In this study, we did not select bare land or the end stage of degraded alpine meadow, but studied alpine meadow with a moderate level of degradation for three reasons. First, alpine meadow with a medium level of degradation occupies a large area of the total grassland in the Qinghai-Tibetan Plateau. Second, bare land cannot be restored quickly or even in hundreds of years because of the extremely cold climate; alpine meadow with a moderate level of degradation can be restored in a short period of time under rational and eco-friendly management. Third, understanding the intermediate processes of alpine meadow degradation will be helpful for revealing the mechanisms causing degradation and provide land managers with the support they need to prevent the further degradation. The intact alpine meadow (IAM) selected for this study forms part of the typical Alpine Meadow typically found in the Qinghai-Tibetan Plateau with >95% vegetation coverage that averages 5 cm tall. The moderately degraded alpine meadow (MDAM) selected here is an area of typical moderately degraded land commonly found in the Qinghai-Tibetan Plateau with about 50–70% vegetation coverage in an area covered where gravel and sand covered 30–50% of the surface.

The experimental site is near the source of the Yangtze River in an inland area of the Qinghai-Tibetan Plateau at 92°55′E, 34°49′N an elevation of 4635 m a.s.l. (Fig. 1). Based on ten recent years (2002–2011) of metrological data from the Beiluhe Weather Station, the mean annual, mean annual maximum, and mean annual minimum air temperatures are −3.8 °C, 19.2 °C, and −27.9 °C, respectively. The mean annual precipitation is 290.9 mm with over 95% falling during the warm growing season from April to October; the mean annual evaporation is 1316.9 mm, mean annual relative humidity is 57%, and mean annual wind velocity is 4.1 m s^{-1}. The site is grazed during the summer and dominated by alpine meadow vegetation such as *Kobresia capillifolia*, *Kobresia pygmaea*, *Carex moorcroftii* with a mean height of 5 cm in the undisturbed ecosystem.

Two 2 m × 2 m plots of MDAM and three 2 m × 2 m plots of IAM, all spaces more than 4 m apart were selected at the experimental site with a distance of about 50 m between the MDAM and IAM blocks. Continuous observation and measurement on soil, plant and microclimate characteristics were conducted in these five plots in 2011 and 2012.

2.2. Temperature and moisture content of air and soil measurements

In each plot, air temperature (T_{air}) and relative humidity (RH_{air}) at 20 cm above the surface were measured by Model HMP45C Vaisala Temperature and Relative Humidity Probes (Campbell Scientific, Logan, UT, USA). Ground surface temperatures (T_{soil_surf}) were measured by SI-111 Apogee 20 Infrared Radiometers (Campbell Scientific, Logan, UT, USA). Soil temperature (T_{soil}) was measured at depths of 20, 40, 60 and 100 cm by Model 109SS-L Temperature Probes (Campbell Scientific, Logan, UT, USA) with an endurance range of −40–100 °C. Soil moisture content (M_{soil})

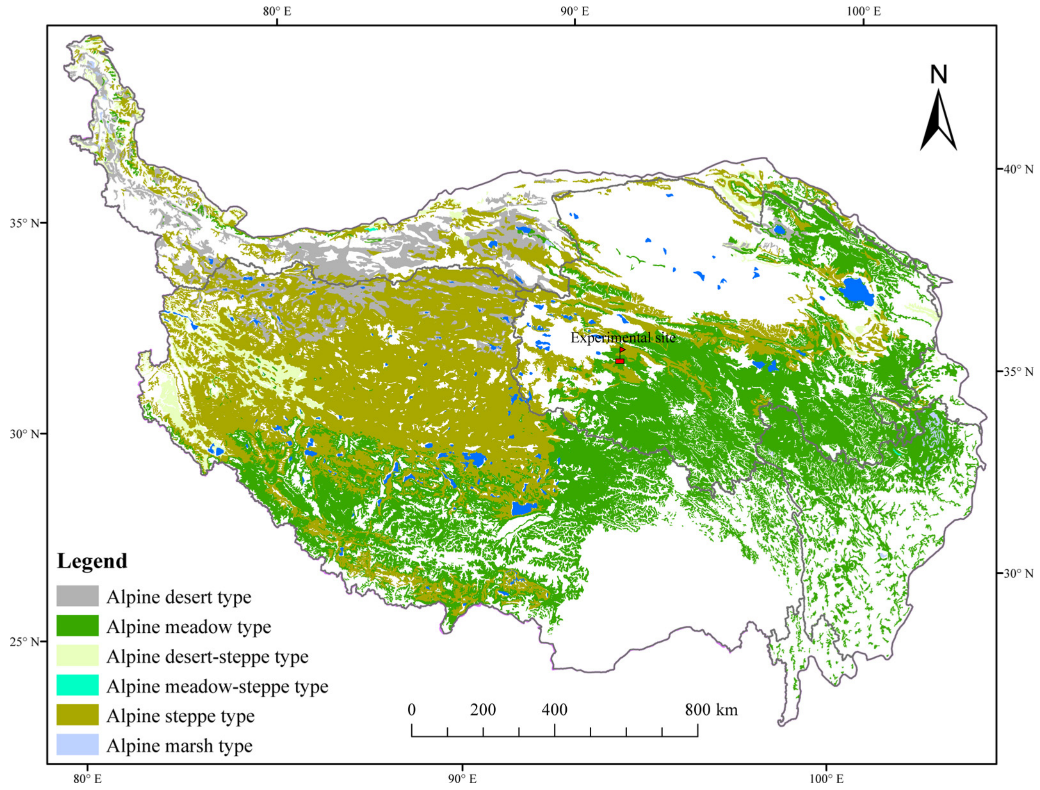

Fig. 1. Grassland types, distribution, and experimental site location in the Qinghai-Tibetan Plateau, China.

at depths of 10, 20, 40, 60, and 100 cm was measured by Envior SMART sensors (Sentek Sensor Technologies, Stepney, Australia) based on frequency domain reflection (FDR). All of the factors were measured continuously with a 10 min recording interval from Jan 1, 2011 to Dec 31, 2012 and were recorded by probes connected to a CR1000 data logger capable of enduring low temperatures (Campbell Scientific Inc., Logan, UT, USA).

The annual mean values for T_{air}, RH_{air}, $T_{\text{soil\_surf}}$, T_{soil} and M_{soil} and their standard deviations in 2011 and 2012 were calculated based on the original 10-min data in each plot. This method provided four replicates for MDAM sites (two in 2011 and two in 2012), and six replicates for IAM sites (three in 2011 and three in 2012).

2.3. Measurement of soil physical and chemical characteristics

Because changes in soil physical and chemical characteristics are not evident over a two-year period, the measurement of soil bulk density (SBD), soil texture (ST), soil organic carbon (SOC), water holding capacity of soil (SWHC), and soil thermal conductivity (STC) were only conducted for once in this study.

First, one soil profile in each MDAM and IAM plot were collected. Then soil samples (inner diameter of the soil corer is 50 mm) with five repetition for each layer were taken from depths of 0–10, 10–20, 20–40, 40–70 and 70–100 cm at both sites. Soil samples were measured for SBD by the core method (Sala et al., 2000) and SOC by the potassium dichromate oxidation titration method (Walkley, 1947) in the Key Laboratory of Desert and Desertification of the Chinese Academy of Sciences (CAS). Part of the same soil samples also were used to measure SWHC by the centrifugal test method (CR21G, Hitachi Inc.) in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau of China. STC was measured by a QL-30 Thermo-physical property analyzer in the State Key Laboratory of Frozen Soil Engineering of China.

Soil samples (inner diameter of the soil corer is 70 mm) were collected as described above from depths of 0–5, 5–10, 10–20, 20–30 and 30–50 cm in the MDAM and IAM and were used to measure ST by a laser-light diffraction instrument (Arriaga et al., 2006). ST usually can be measured as the percentage of fine and coarse particles as part of the total particle content. In this study, the content of the particles of different sizes were measured and analyzed; then we classified the particles with the size $>$ and $\leq$0.125 mm as either coarse or fine particles, respectively.

2.4. Measurement of vegetation characteristics

Vegetation characteristics, including height (VH), coverage (VC) and species number (SN), aboveground and belowground biomass (M_a and M_b), in five experimental plots (two MDAM plots and three IAM plots) were measured in May, June, July, August and September of 2011 and 2012.

Each plot was first divided evenly into four 1 m × 1 m sections. Then the section was divided into 100 subplots, each 10 cm × 10 cm. Ten subplots in each section were randomly selected and the plants names, numbers and heights were measured and recorded.

VC was measured using a 27 cm × 27 cm frame (interior dimensions) and a hard iron net with a grid of 100 subplots. The frame was randomly set into one section. At each grid intersection on the net, ground cover was recorded as either bare ground, litter or a plant. The proportion of coverage for each of the three ground cover types was calculated by the number of hits of bare ground, litter or plants divided by 100. In each plot, VC of four sections was measured, and then the mean VC of the four sections was calculated for the plot.

To calculate M_a in each experimental plot without destroying the vegetation, five temporary plots with different VC and VH were selected outside the experimental plots. M_a in the five temporary plots was measured by cutting, drying (48 h to a constant weight at 75 °C) and weighing the aboveground growth in a 20 cm × 20 cm area for each temporary plot. Other vegetative characteristics were measured five times each year in the experimental plots. In 2011, the M_a was measured 12 times and another 8 times in 2012 in the five temporary plots for a total of 100 M_a measurements. Then the relation function between M_a, VH and VC was established (Function 1). Based on the function and the measured VH and VC in the five experimental plots, M_a in the MDAM and the IAM were calculated using Eq. (1).

$$M_a = 308.26\mathrm{VC} + 22.764\mathrm{VH} - 121.801$$
$$\left(r^2 = 0.737, \quad P < 0.001, \quad n = 100\right) \tag{1}$$

For measuring M_b of the five experimental plots, soil samples with roots were collected in the experimental plots using a 7 mm inside diameter soil corer at depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–50 cm. Next, the samples were immediately transported to the laboratory in a cooler. In the laboratory, root and soil samples were air-dried, crumbled and sieved. Then, larger roots were separated from the soil and the washed soil was filtered with a 0.25 mm sieve to retrieve fine roots. Live roots were distinguished from dead roots by their colors, consistency and presence of attached fine roots; M_b in each experimental plot can be calculated by drying and weighing the soil (Yang et al., 2009b).

2.5. Soil respiration measurements

Soil respiration (R_s) including autotrophic respiration (R_a) from plant roots and their symbionts, heterotrophic respiration (R_h) from litter and SOC were measured in the May, June, July, August and September of 2011 and 2012. To measure R_s, 5 cm tall, 10 cm diameter PVC collars with an area of 80 cm^2 were permanently inserted 2–3 cm into soil at the center of each plot. Small living plants were removed at the soil surface at least 1 day before measurements to eliminate the effect of aboveground biomass respiration. To measure the R_h, 50 cm long PVC tubes (10 cm in diameter and 80 cm^2 in area) were inserted in each plot near the shallow collars prior to measurement. The deep PVC tubes cut off old plant roots (mainly distributed at depths of 0–30 cm in soil) and prevented new roots from growing inside the tubes. CO_2 efflux measured above the deep tubes represented R_h three months after the deep collar had been inserted. R_a was calculated as the difference between R_s and R_h, which was measured once or twice a month between 10:00 and 15:00 h (local time), using an Li-Cor 6400 portable photosynthesis system attached to soil CO_2 flux chamber (Li-Cor, Inc., Lincoln, NE, USA.).

2.6. Statistical analysis

There were two plots for MDAM and three plots for IAM in the study. Soil samples with five repetitions for each layer in each plot

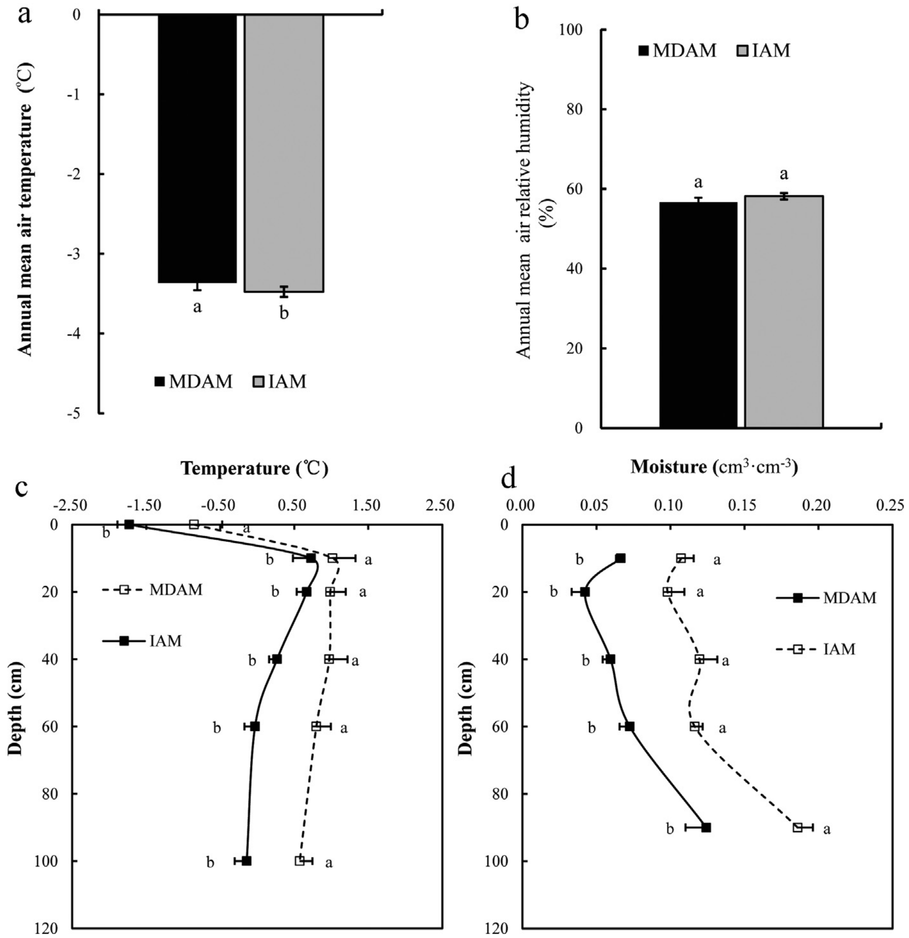

Fig. 2. The air temperature, relative humidity as well as soil temperature and moisture in moderately degraded (MDAM) and intact alpine meadow (IAM). Different letters indicate statistically significant differences at the corresponding *P*-values, and the same letters indicate statistical insignificant differences at *P* > 0.05 between DAM and IAM, as determined by ANOVA. Bars indicate standard errors.

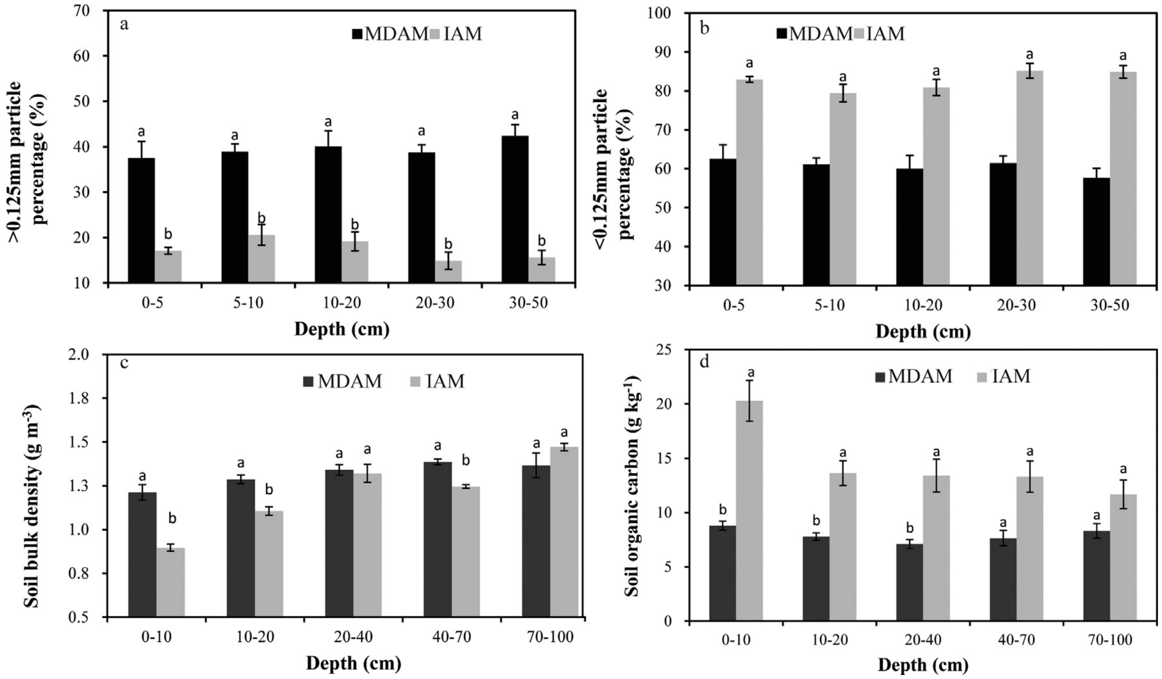

Fig. 3. Soil texture (particle size distribution), soil bulk density and soil organic carbon in the moderately degraded (MDAM) and intact alpine meadow (IAM). Different letters indicate statistically significant differences at the corresponding *P*-values, and the same letters indicate statistical insignificant differences at $P > 0.05$ between MDAM and IAM, as determined by ANOVA. Bars indicate standard errors.

were taken for measuring soil physical and chemical characters. Therefore, there were ten soil characters measurement repetitions for MDAM and 15 repetitions for IAM. Five measurements were conducted for vegetation characters and soil respiration each year for 2011 and 2012. Therefore, there are 20 repetitions for MDAM and 30 repetitions for IAM. One-way ANOVAs were used with significance levels of 0.05 and 0.01 to evaluate the statistical significance of variations in degraded and intact alpine meadow for all of the factors analyzed here using SPSS 16.0 for Windows. Basing on the simple linear and nonlinear regression methods, the relationships among different soil and vegetation characteristics were analyzed using Origin 9.0 software.

3. Results

3.1. Air and soil temperature and moisture comparisons in MDAM and IAM

The annual mean T_{air} 20 cm above the surface was $-3.37 \pm 0.09\,^{\circ}$C in the MDAM and $-3.48 \pm 0.06\,^{\circ}$C in IAM. Air temperature in MDAM was significantly ($P = 0.004$) higher than that in IAM (Fig. 2a). The annual mean RH_{air} at the same height was 56.67 ± 1.10% in the MDAM and 58.16 ± 0.81% in IAM. Atmosphere relative humidity in MDAM was insignificantly ($P = 0.407$) lower than that in IAM (Fig. 2b), while the annual maximum RH_{air} in the MDAM (83.54 ± 0.85%) was significantly ($P = 0.048$) lower than that in the IAM (84.83 ± 0.50%). Fig. 2c and d presents the temperature and moisture in the soil profile in MDAM and IAM. Following the same pattern observed with T_{air}, T_{soil} in the depths of 0, 10, 20, 40, 60 and 100 cm were −0.85 ± 0.38, 1.02 ± 0.31, 0.99 ± 0.21, 0.97 ± 0.25, 0.80 ± 0.20 and 0.57 ± 0.17 °C in MDAM, and were −1.73 ± 0.16, 0.73 ± 0.25, 0.67 ± 0.14, 0.27 ± 0.11, −0.03 ± 0.14 and −0.14 ± 0.16 °C in IAM. Soil temperatures in MDAM were significantly ($P = 0.000$) higher than those in IAM. M_{soil} in the depths of 10, 20, 40, 60 and 90 cm were 6.7 ± 0.3, 4.2 ± 0.9, 6.0 ± 0.5, 7.3 ± 0.7, 12.4 ± 1.4% in MDAM, and were 10.7 ± 0.8, 9.8 ± 1.1, 12.0 ± 1.2, 11.6 ± 0.5, 18.6 ± 1.0% in IAM. Soil moistures in MDAM were significantly ($P = 0.000$) lower than those in IAM. From the above observational data, it can be seen that the atmosphere near surface and soil in the MDAM was warmer and drier than that in the IAM.

3.2. Comparisons of soil physicochemical characteristics in MDAM and IAM

In the entire soil profile from depths of 0 to 50 cm, the percentage of coarse particles (size >0.125 mm) in the depths of 0–5, 5–10, 10–20, 20–30 and 30–50 cm were 37.52 ± 3.64, 38.90 ± 1.68, 40.05 ± 3.43, 38.76 ± 1.68 and 42.38 ± 2.45% in the MDAM, and were 17.09 ± 0.76, 20.59 ± 2.29, 19.15 ± 2.07, 14.88 ± 1.90 and 15.60 ± 1.59% in IAM. The percentage of coarse particles in MDAM were significantly ($P = 0.000$) higher than that in the IAM. The percentage of fine particles (size <0.125 mm) in the depths of 0–5, 5–10, 10–20, 20–30 and 30–50 cm were 62.52 ± 3.64, 61.10 ± 1.68, 60.03 ± 3.43, 61.45 ± 1.81 and 57.67 ± 2.45% in the MDAM and were 82.95 ± 0.76, 79.41 ± 2.29, 80.88 ± 2.07, 85.18 ± 1.90 and 84.88 ± 1.58% in IAM. The percentage of fine particles were significantly ($P = 0.000$) lower than that in the IAM (Fig. 3a and b), respectively.

SBD in the depths of 0–10 cm, 10–20 cm and 40–70 cm in the MDAM (1.21 ± 0.044, 1.29 ± 0.02, and 1.39 ± 0.03 g m^{-3}) were significantly ($P = 0.001$, $P = 0.001$ and $P = 0.002$) higher than that in the IAM (0.90 ± 0.02, 1.11 ± 0.02 and 1.25 ± 0.01 g m^{-3}). In the depths of 20–40 cm and 70–100 cm, SBD in the MDAM (1.34 ± 0.03 and 1.37 ± 0.07 g m^{-3}) was non-significantly different ($P = 0.786$ and $P = 0.229$, respectively) with that in the IAM (1.32 ± 0.10 and 1.47 ± 0.02 g m^{-3}) (Fig. 3c).

SOC at the depths of 0–10 cm, 10–20 cm and 20–40 cm were 8.79 ± 0.41, 7.79 ± 0.34 and 7.11 ± 0.42 g kg^{-1}in the MDAM, and were 20.29 ± 1.88, 13.64 ± 1.14 and 13.41 ± 1.51 g kg^{-1} in IAM. SOC in MDAM were significantly lower than that in the IAM at the depths of 0–10 cm ($P = 0.000$), 10–20 cm ($P = 0.001$) and 20–40 cm

Table 1
The plant height, coverage, species diversity, aboveground biomass, and belowground biomass in moderately degraded and intact alpine meadow.

Type	VH (cm)	VC (%)	SN (kinds)	M_a (g m^{-2})	$M_{b\,0\text{–}50}$ (g m^{-2})	$M_{b\,0\text{–}10}$ (g m^{-2})	$M_{b\,10\text{–}20}$ (g m^{-2})	$M_{b\,20\text{–}30}$ (g m^{-2})	$M_{b\,30\text{–}40}$ (g m^{-2})	$M_{b\,40\text{–}50}$ (g m^{-2})
MDAM	6.30 ± 0.28a	65.40 ± 4.22b	11 ± 0.5a	222.76 ± 17.75a	4648.35 ± 420.64a	1815.73 ± 57.93b	1100.85 ± 93.76b	829.86 ± 152.05a	579.16 ± 102.07a	322.74 ± 58.39a
IAM	4.70 ± 0.26b	84.90 ± 1.84a	8 ± 0.4b	247.20 ± 10.91a	5170.04 ± 335.11a	2637.35 ± 171.50a	1351.09 ± 117.50a	691.74 ± 76.40a	349.27 ± 42.73b	140.59 ± 23.84b

Note: abbreviations include: MDAM, moderately degraded alpine meadow; IAM, intact alpine meadow; VH, vegetation height; VC, vegetation coverage; SN, plant species number; M_a, aboveground biomass; M_b, below ground biomass. Different letters indicate statistically significant differences at the corresponding *P*-values, and the same letters indicate statistical insignificant differences at $P > 0.05$ between MDAM and IAM, as determined by ANOVA; ± indicate standard errors.

($P = 0.006$). In the depths of 40–70 cm and 70–100 cm, although, the SOC in the MDAM (7.65 ± 0.72 and 8.31 ± 0.67 g kg^{-1}) were insignificantly ($P = 0.100$ and $P = 0.710$, respectively) lower than that in the IAM (13.32 ± 1.44 and 11.69 ± 1.32 g kg^{-1}) (Fig. 3d).

3.3. Comparison of vegetative characteristics in DAM and IAM

Fig. 4 shows the percentage of different species plant numbers occupied the total plant numbers in MDAN and IAM. It can be seen that *K. pygmaea*, *Kobresia humilis*, *K. capillifolia*, *Carex atrofusca* and *Oxytropis pusilla* were predominant species, and *Poa alpina*, *Leontopodium nanum*, and *Polygonum sibiricum* were companion species in the IAM. In the MDAM, the number of *K. pygmaea*, *K. capillifolia*, and *C. atrofusca* decreased, *Saussurea haoi* became absolutely dominant, with the companion species included *Ajania tenuifolia, Androsace gmelinii* and *Roripa montana*. VH and SN of the vegetation were 6.30 ± 0.28 cm and 11.0 ± 0.5, respectively, in the MDAM and were 4.70 ± 0.26 cm and 8.0 ± 0.39, respectively, in IAM. VH and SN in the MDAM were significantly ($P = 0.002$ and $P = 0.001$) higher than that in the IAM, while VC in MDAM ($65.4 \pm 4.22\%$) was significantly ($P = 0.000$) lower than that in the IAM ($84.9 \pm 1.84\%$), and B_a in the MDAM (222.76 ± 17.75 g m^{-2}) was non-significantly ($P = 0.128$) lower than that in the IAM (247.2 ± 10.91 g m^{-2}) (Table 1).

M_b at depth of 0–50 cm was 4648.35 ± 420.64 g m^{-2} in MDAM, 5170.04 ± 335.11 g m^{-2} in IAM, and M_b in MDAM was non-significantly lower than that in the IAM. At depths of 0–10 cm and 10–20 cm, M_b in MDAM was significantly ($P = 0.000$ and $P = 0.039$) lower than that in the IAM. At depths of 20–30 cm, M_b in MDAM was insignificantly ($P = 0.349$) higher than that in the IAM; then at depths of 30–40 cm and 40–50 cm, M_b in MDAM was significantly ($P = 0.045$ and $P = 0.021$) higher than that in the IAM (Table 1).

3.4. Comparisons of soil respiration in MDAM and IAM

There was an evident seasonal change in soil respiration in that the thaw of frozen soil and the plants growing during the summer caused R_s, R_h, and R_a to reach their maximum values in MDAM and IAM in summer (Fig. 5a–c). Unlike other soil characteristics with significant differences, the difference in soil respiration between the MDAM and the IAM were not significant. However, R_s and R_h in the MDAM were higher than that in the IAM for each month. The difference between MDAM and IAM rapidly increased from May to July, and reached the maximum difference in July, then remained stable in August and September. R_a in the MDAM were lower than that in the IAM in May, June, August, and September, but higher in July (Fig. 5c). Fig. 5d shows the average soil respiration from May to September of 2011 and 2012, showing that R_s and R_h in the MDAM were insignificantly higher than that in the IAM, and R_a in the MDAM were insignificantly lower than that in the IAM.

4. Discussion

4.1. Vegetation degradation and its cause in alpine meadows

Important differences in vegetation characteristics can be found between MDAM and the IAM habitats. The *Kobresia* species with high VC and low VH were substituted by the *Spenceria* species with low VC and high VH, which caused the significant difference in VH, VC and SN between MDAM and IAM. The insignificant change of M_a can be attributed to the high VH compensating for the low VC. Nevertheless, pasture productivity in MDAM was lower due to the lower protein and nutrient content of weeds compared with that in IAM (DAHVGS and GSAHV, 1996). The degradation of alpine meadow can directly affect the livelihood of the local herdsman,

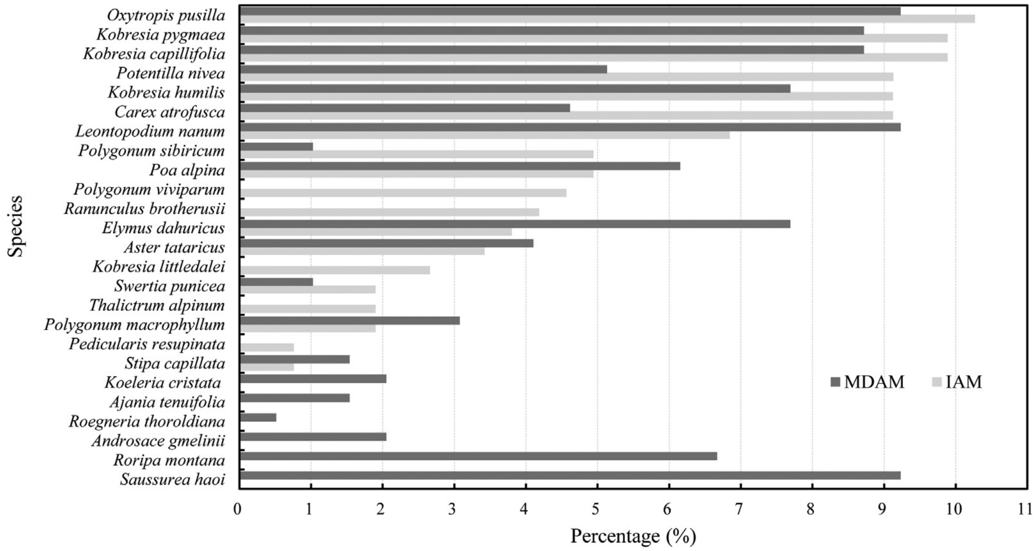

Fig. 4. The percentage of the plants numbers for each species as a fraction of the total numbers of plants of all of species in the moderately degraded (MDAM) and intact alpine meadow (IAM).

although the change of M_a was not evident. Therefore, the criteria for evaluation the degradation of the alpine meadow depends on more than simply the change of M_a.

The difference of vegetation types between MDAM and IAM also affects the change of M_b. Compared to *Kobresia* species with shallow roots, *Spenceria* species and some weeds have relatively deep roots. The increasing abundance of *Spenceria* species and some weeds and the decreasing abundance of *Kobresia* species in MDAM caused a significant change in M_b. In the soil profile, M_b in MDAM varied from significantly lower, insignificantly lower, insignificantly higher, and then significantly higher than that in IAM with increasing depth, which indicated the replacement of grass with shallow roots by weeds with deep roots in MDAM. This pattern is consistent with the increasing height of plants in MDAM. Yang et al. (2009b) investigated the biomass of 141 sites and determined the isometric allocation of above- and below-ground biomass in alpine grasslands on the Qinghai-Tibetan Plateau. Our results not only support this conclusion, also further propose a new hypothesis for the relationship between plant height and root depth. Namely, the possibly exists that there is a positive correlation between plant height and plant root depth in the alpine meadow ecosystem.

The factors affecting the changes in vegetation types between MDAM and IAM were analyzed. *Kobresia* species are dominant plants in cold and wet environments. In contrast, *Spenceria* species and weeds have a relatively high capability to resist drought because their deep roots can get more water from deep soil

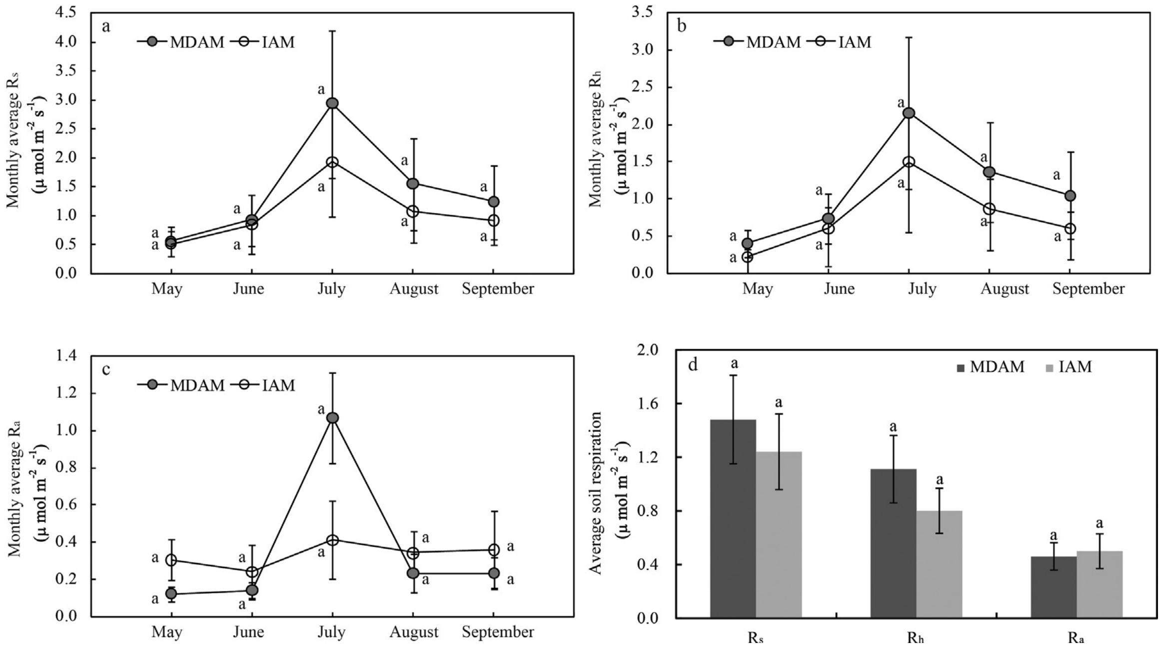

Fig. 5. The monthly average soil total (R_s, a), heterotrophic (R_h, b) and autotrophic (R_a, c) respiration during 2011 and 2012, and the average soil total respiration for May, Jun, July, August, and September of 2011 and 2012 (d) in the moderately degraded (MDAM) and intact alpine meadow (IAM). The same letters indicate statistical insignificant differences at $P > 0.05$ between MDAM and IAM, as determined by ANOVA. Bars indicate standard errors.

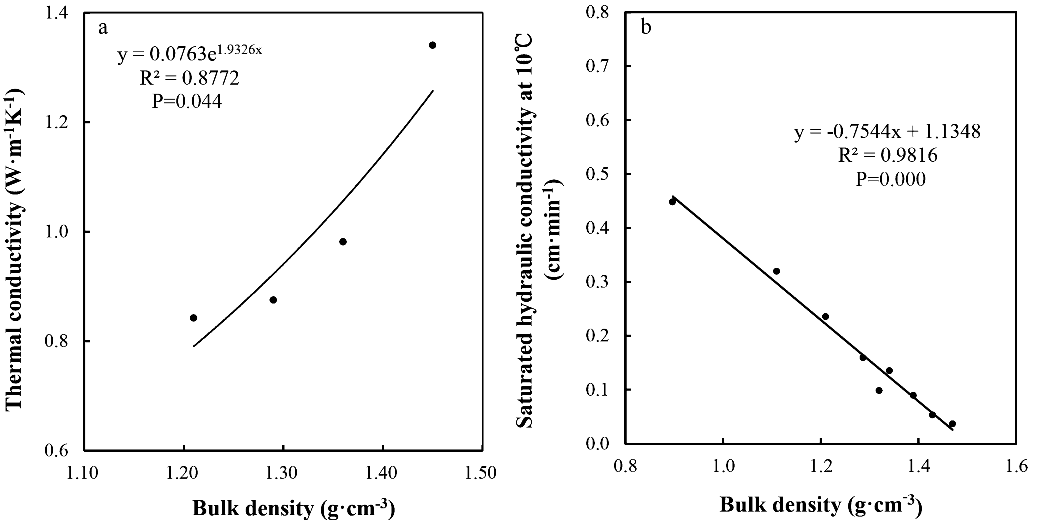

Fig. 6. The relationship analysis among soil bulk density, thermal conductivity and saturated hydraulic conductivity.

layers. The increased soil temperatures caused by coarsen particles and degraded soil physical characteristics (Fig. 2c) in a way that can result in increased evaporation and infiltration of water into the deep soil layers after more frozen water thaws in alpine region, accordingly reducing the moisture content of surface soil while precipitation remains stable or experiences weak variations in the Plateau (Fig. 2c). Dry surface soil cannot support vegetation with shallow roots, allowing vegetation with deep roots to gradually become dominant. Therefore, drought in the shallow soil layer may be the main cause of vegetation degradation. Many publications have presented a close relation between plant community composition and soil moisture in the other regions of the world (Paul and Harrison, 1982; Breshears and Barnes, 1999; Knapp et al., 2002; Walker et al., 2006; Wu et al., 2013). Some field observations conducted in different grades of desertified alpine meadowlands of the Qinghai-Tibetan Plateau also proved that the original plants of alpine meadow were gradually replaced by the xerophytic plants with an increase of degradation (Xue et al., 2009; Wu et al., 2013).

Usually, drought is controlled by temperature and precipitation. Increased precipitation can compensate for water lost from the surface soil from evaporation and infiltration, and is beneficial to the accumulation of biomass in alpine meadows giving them an

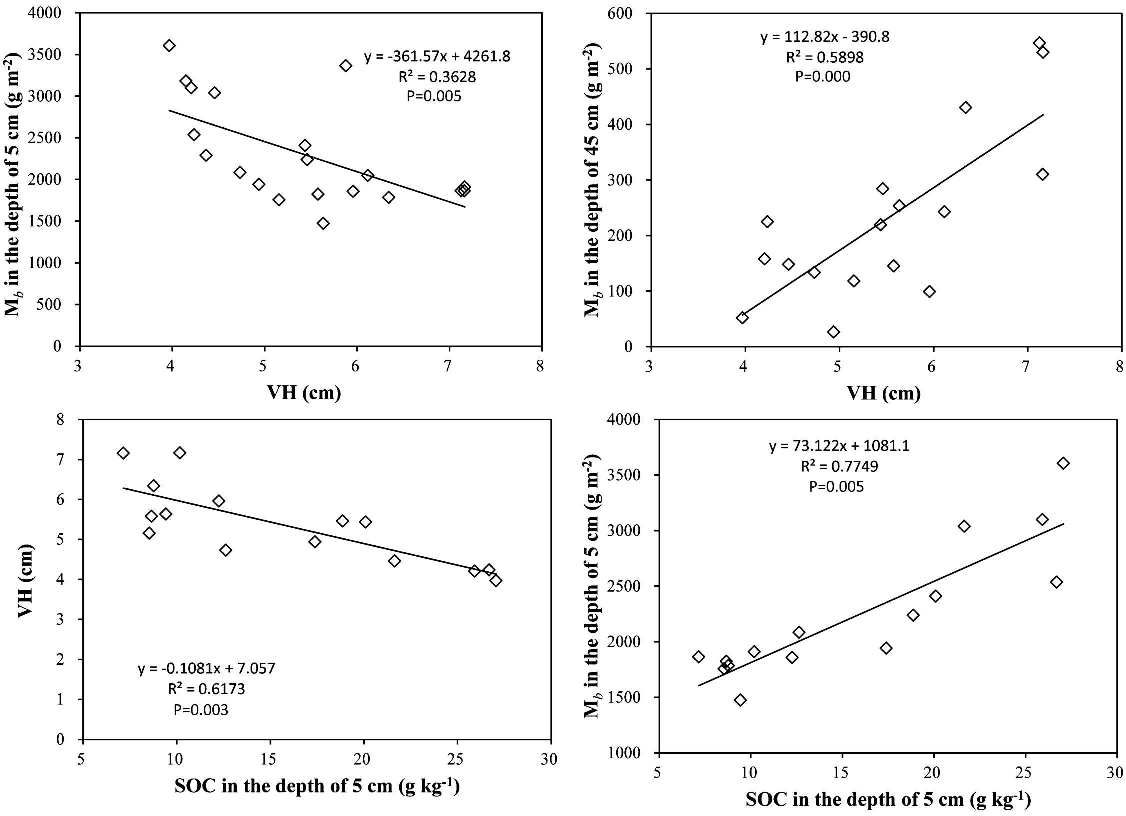

Fig. 7. The relationship analysis among V_h, SOC and M_b at different soil depths.

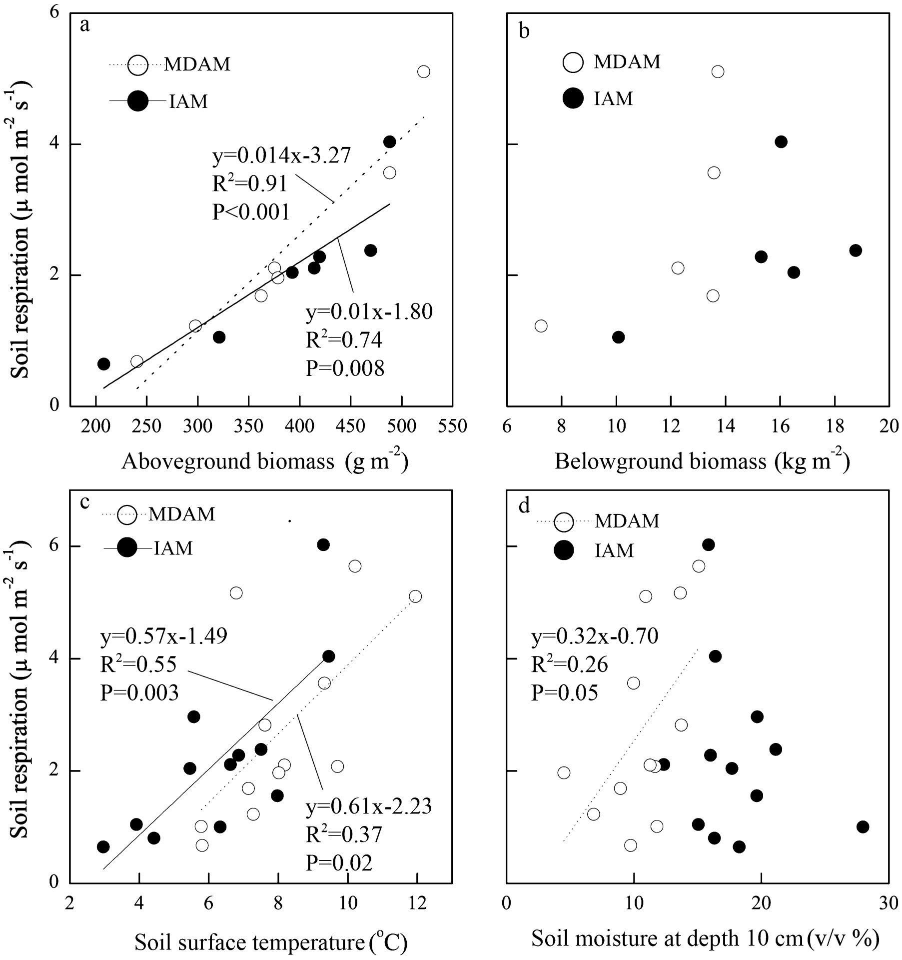

Fig. 8. The relationship analysis among R_s, M_a, M_b at soil depths 0–50 cm, soil surface temperature, soil moisture at depth 10 cm.

advantage of increased productivity. In contrast, low precipitation can intensify drought and exacerbate land degradation caused by warming.

4.2. Degradation of soil physical characteristics and the biogeochemical cycle in MDAM

The main cause of soils having coarse particles and degraded soil physical characteristics in arid regions is a lack of vegetation coverage, because fine particles can be eroded by wind and water when the soil surface loses the protection of vegetation. This point can be proven by the low VC and high percentage of the coarse particle (Fig. 3 and Table 1). In addition, the influence of M_b and the roots on the ST is worth noticing, because it is very unique in the MDAM. As described above, the shallow turf layer with dense root in alpine meadows can protect the soil fine particles from wind and water erosion. A simulation experiment in a wind tunnel shows that intact alpine meadows have the highest soil conservation function among the alpine meadow, alpine steppe and alpine steppe-meadow (Lu et al., 2013). In MDAM, plants with shallow roots had been replaced by plants with deep roots, which caused the degradation of the turf layer. The degraded turf layer weakened the ability of the root layer to prevent wind and water erosion, therefore resulting in the degradation of ST.

Land degradation usually increases SBD because the increased abundance in coarse particles and the reduction in available water-holding capacity results in increased degradation (Lal, 1996; Islam and Weil, 2000; García-Orenes et al., 2005). The variation of SBD between the MDAM and the IAM at depths of 0–70 cm in our study was consistent with the pattern observed in other regions. However, in our research, SBD at depth of 70–100 cm in the MDAM was insignificantly lower than that in the IAM. This pattern can be explained by the difference of root content between the MDAM and the IAM. With increasing depth, the root content relatively increased in the MDAM, which resulted in a lower SBD in deep soil, when compared with that in the IAM.

With the degradation of soil physical characteristics, SWHC decreased and intensified the loss of soil moisture from evaporation and infiltration in the shallow soil layer in the MDAM. The reduced M_{soil} decreased the soil heat capacity and increased STC (Fig. 6), which led the T_{soil} and T_{air} in the MDAM being significantly higher than that in the IAM (Fig. 2). The higher T_{soil}, T_{air} and the lower M_{soil} in the MDAM can intensify the process of degradation because dry soil further encourages the development of the vegetation with deep roots. However, with the increased evaporation and infiltration caused by climate warming and overgrazing over a long period of time, the vegetation will disappear when it cannot acquire an adequate supply of water, and the alpine meadow will move into the fully degraded stage. Without outside help, alpine meadows will fall into a vicious cycle of land degradation. Therefore, taking some measures to control overgrazing and alleviate the impact of climate warming on alpine meadow ecosystem is vitally important.

4.3. The influence of land degradation on carbon release in alpine meadows

Based on warming experiments, field surveys and modeling studies, some researchers believe that land degradation caused by climate warming in the Qinghai-Tibetan Plateau will increase concentration of atmospheric CO_2. This may amplify surface warming and initiate a positive carbon feedback loop as increased thawing leads to the releases of carbon previously frozen in permafrost and seasonal frozen soil (Wang et al., 2002; Lin et al., 2011; Schaefer et al., 2011; Cheng and Wu, 2007). However, Yang et al. (2009b) pointed out that great uncertainties exist in changes of soil carbon driven by warming on the Plateau because the increased rates of decomposition occurring as soils warmed may be compensated for by increased soil C inputs caused by increased grass productivity. Our result shows a significant decrease in SOC occurs in the topsoil of the MDAM, but a significant correlation between SOC and T_{soil} in the same soil layers was not observed; nevertheless, a significant correlation was found between the SOC and M_b at depth of 5 cm ($r^2 = 0.7749$, $P < 0.01$) (Fig. 7d). This pattern implied the decreased SOC in the topsoil of the MDAM did not necessarily depend entirely on the increasing decomposition rate driven by the increasing T_{soil}. The decreasing M_b and grass productivity in the topsoil may play a role that cannot be ignored in affecting the SOC. Our findings are consistent with those of Yang et al. (2009b) who explained the influence of grass productivity on the SOC, although they concluded that the SOC stock in the Qinghai-Tibetan Plateau remained relatively stable during the 1980s to 2004 with a 46.7% decrease in spatial extent of alpine meadow.

To gain a better understanding how carbon release is driven by decomposition and plant activities, we compared the soil R_h and R_a in the MDAM and IAM. The results show that R_h from the decomposition of the litter and SOC in MDAM increased insignificantly and R_a decreased insignificantly. Degraded alpine meadow had a higher surface and soil temperature, which can encourage the decomposition of litter and soil microbe. Therefore, R_h in MDAM is higher than that in IAM. The thaw of seasonal frozen soil accelerated the decomposition process and resulted in an increasing trend of R_h and R_s causing a difference between MDAM and IAM from May to July. R_a mainly depends on plant respiration processes. Degraded alpine meadow had a lower M_a and total M_b (Table 1), which resulted in a reduction of plant respiration and lower R_a in MDAM in May, June, August and September. However, R_a in MDAM was higher than that in IAM in July. This pattern probably is attributed to the change in species in degraded habitat. *Kobresia* species were replaced by *Spenceria* species and weeds with deep root systems in MDAM. It is worth noticing that *Spenceria* species and weeds, especially weeds, have wide leaves than *Kobresia* species, which may result in an increase in plant respiration during July.

To prove the above explanation, the relationship of soil respiration with biotic and abiotic factors was analyzed (Fig. 8). Among four factors (aboveground biomass, belowground biomass, soil surface temperature and soil moisture at depth 10 cm), aboveground biomass had the strongest correlation with soil respiration, which indicates the effect of fresh carbohydrates from photosynthesis on the soil respiration. Soil temperature is the second important factor affecting soil respiration in degraded alpine meadow ecosystems. Soil respiration was positively correlated with soil moisture only in the MDAM, which suggests that the constraints soil moisture places on soil respiration only occurs while soil moisture was significantly low (Fig. 8d). Therefore, degradation induced the reduction of aboveground mass, caused an increase in soil temperature, and caused a reduction in surface soil moisture that resulted in an increase of S_h and a decrease of R_a in MDAM. The insignificance of change may be attributed to the lower rates of degradation.

5. Conclusions

Land degradation is a comprehensive system process. Once degradation is driven by climate change or human activities, all kinds of ecosystem factors will become involved in the process and affect changes in the ecosystem through positive or negative feedback and their interaction. Nevertheless, it is not clear how the relationships among different factors and how these factors themselves interact to affect ecosystem degradation, especially in an alpine region where the ecosystem is sensitive to climatic warming and human activities. Based on field observation related to different factors and an analysis for their relationships, this study reveals the mechanisms involved in alpine meadow ecosystem degradation and concluded two processes affect ecosystem development.

(1) First, warming induced by climate change increased soil temperatures and caused drought in the surface soil by increasing evaporation rates and the loss of soil moisture from infiltration. Then, drought of surface soil resulted in a change in the type of plant community present resulted in a decrease in plant coverage and biomass. Degraded vegetation cannot effectively prevent wind and water erosion, which caused the loss of soil fine particles and soil organic matter. Degradation of soil physical and chemical characteristics intensified warming and drying trends of soil because of the increase in water and heat conductivity. This is a vicious circle of land degradation that is driven by increasing temperatures.

(2) Overgrazing directly destroyed vegetation and resulted in decreased vegetation coverage and biomass. Loss of vegetative protection allowed a marked increase in wind and water erosion and resulted in the coarsening of soil particles and a reduction of soil organic matter, which can alter soil heat and water conductivity, and dry surface soil. Drought within surface soil further induced additional vegetation degradation and changed the plant community. This is a vicious circle of land degradation that is driven by vegetation degradation.

Based on these two types of process, one can conclude that drought causes the loss of plants with shallow roots and these are replaced with deep-rooted plants; this is the main cause of degradation of the alpine meadow ecosystems of the Qinghai-Tibetan Plateau, which fundamentally affected the change of physical, chemical and thermal characteristics of soil. The balance between soil temperature and moisture is a crucial factor affecting land degradation. The change in aboveground mass, soil temperature, and surface soil moisture directly affects carbon release in alpine meadows.

Acknowledgements

This research was financially supported by the One Hundred Talents Program of the Chinese Academy of Sciences. The authors would like to thank Prof. Yongzhi Liu and all the staff at Beiluhe Station for their kind help in the field and for providing the experimental site. The authors would also like to thank the language editors of LetPub Company, anonymous reviewers and an editor for their help and suggestions.

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