Effects of long-term warming on the aboveground biomass and species diversity in an alpine meadow on the Qinghai-Tibetan Plateau of China (Postprint)

Authors: WEN Jing, QIN Ruimin, ZHANG Shixiong, Xiaoyan Yang, XU Manhou, XU Manhou

Date: 2020-06-22T00:00:00+00:00

Abstract

Ecosystems in high-altitude regions are more sensitive and respond more rapidly than other ecosystems to global climate warming. The Qinghai-Tibet Plateau (QTP) of China is an ecologically fragile zone that is sensitive to global climate warming. It is of great importance to study the changes in aboveground biomass and species diversity of alpine meadows on the QTP under predicted future climate warming. In this study, we selected an alpine meadow on the QTP as the study object and used infrared radiators as the warming device for a simulation experiment over eight years (2011-2018). We then analyzed the dynamic changes in aboveground biomass and species diversity of the alpine meadow at different time scales, including an early stage of warming (2011-2013) and a late stage of warming (2016-2018), in order to explore the response of alpine meadows to short-term (three years) and long-term warming (eight years). The results showed that the short-term warming increased air temperature by 0.31°C and decreased relative humidity by 2.54%, resulting in the air being warmer and drier. The long-term warming increased air temperature and relative humidity by 0.19°C and 1.47%, respectively, and the air tended to be warmer and wetter. The short-term warming increased soil temperature by 2.44°C and decreased soil moisture by 12.47%, whereas the long-term warming increased soil temperature by 1.76°C and decreased soil moisture by 9.90%. This caused the shallow soil layer to become warmer and drier under both short-term and long-term warming. Furthermore, the degree of soil drought was alleviated with increased warming duration. Under the long-term warming, the importance value and aboveground biomass of plants in different families changed. The importance values of grasses and sedges decreased by 47.56% and 3.67%, respectively, while the importance value of weeds increased by 1.37%. Aboveground biomass of grasses decreased by 36.55%, while those of sedges and weeds increased by 8.09% and 15.24%, respectively. The increase in temperature had a non-significant effect on species diversity. The species diversity indices increased at the early stage of warming and decreased at the late stage of warming, but none of them reached significant levels (P>0.05). Species diversity had no significant correlation with soil temperature and soil moisture under both short-term and long-term warming. Soil temperature and aboveground biomass were positively correlated in the control plots (P=0.014), but negatively correlated under the long-term warming (P=0.013). Therefore, eight years of warming aggravated drought in the shallow soil layer, which is beneficial for the growth of weeds but not for the growth of grasses. Warming changed the structure of alpine meadow communities and had a certain impact on the community species diversity. Our studies have great significance for the protection and effective utilization of alpine vegetation, as well as for the prevention of grassland degradation or desertification in high-altitude regions.

Full Text

Preamble

Effects of Long-Term Warming on Aboveground Biomass and Species Diversity in an Alpine Meadow on the Qinghai-Tibetan Plateau of China

WEN Jing, QIN Ruimin, ZHANG Shixiong, YANG Xiaoyan, XU Manhou*
Taiyuan Normal University, Jinzhong 030619, China

Abstract: Ecosystems in high-altitude regions are more sensitive and respond more rapidly to global climate warming than other ecosystems. The Qinghai-Tibet Plateau (QTP) of China is an ecologically fragile zone that is particularly sensitive to global climate warming. Studying changes in aboveground biomass and species diversity of alpine meadows on the QTP under predicted future warming scenarios is therefore of great importance. In this study, we selected an alpine meadow on the QTP as our research object and used infrared radiators as warming devices in a simulation experiment conducted over eight years (2011–2018). We analyzed the dynamic changes in aboveground biomass and species diversity at different time scales, including an early warming stage (2011–2013) and a late warming stage (2016–2018), to explore the responses of alpine meadows to short-term (three years) and long-term (eight years) warming. The results showed that short-term warming increased air temperature by 0.31°C and decreased relative humidity by 2.54%, making the air warmer and drier. Long-term warming increased air temperature and relative humidity by 0.19°C and 1.47%, respectively, making the air warmer and wetter. Short-term warming increased soil temperature by 2.44°C and decreased soil moisture by 12.47%, whereas long-term warming increased soil temperature by 1.76°C and decreased soil moisture by 9.90%. This caused the shallow soil layer to become warmer and drier under both short-term and long-term warming, though the degree of soil drought was alleviated with increased warming duration. Under long-term warming, the importance values and aboveground biomass of plants in different families changed. The importance values of grasses and sedges decreased by 47.56% and 3.67%, respectively, while the importance value of weeds increased by 1.37%. Aboveground biomass of grasses decreased by 36.55%, while those of sedges and weeds increased by 8.09% and 15.24%, respectively. Warming had a non-significant effect on species diversity. The species diversity indices increased in the early stage of warming and decreased in the late stage, but none reached significant levels (P>0.05). Species diversity showed no significant correlation with soil temperature or soil moisture under either short-term or long-term warming. Soil temperature and aboveground biomass were positively correlated in the control plots (P=0.014) but negatively correlated under long-term warming (P=0.013). Therefore, eight years of warming aggravated drought in the shallow soil layer, which benefited weed growth but not grass growth. Warming changed the structure of alpine meadow communities and had a certain impact on community species diversity. Our findings have great significance for the protection and effective utilization of alpine vegetation, as well as for the prevention of grassland degradation or desertification in high-altitude regions.

Keywords: climate warming; long-term warming; species diversity indices; aboveground biomass; soil microclimate; correlation analysis; alpine meadows

*Corresponding author: XU Manhou (E-mail: xumanhou@163.com)
Received 2019-05-13; revised 2020-01-16; accepted 2020-01-23

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2014) indicated in its Fifth Assessment Report that global mean surface temperature increased by 0.85°C from 1880 to 2012 [?, ?]. It is an indisputable fact that the Earth has become warmer [?, ?]. Climate warming profoundly affects the structural characteristics and processes of grassland ecosystems [?, ?], which provide important ecosystem services [?, ?]. Studying changes in plant biomass and species diversity and their significance under predicted future climate warming is therefore of great importance [?, ?, ?].

Aboveground biomass, as the product of interactions between plant characteristics and habitats, is a principal index for assessing ecosystem structure and function and has a profound impact on grassland livestock husbandry [?, ?]. It has become an important aspect of biomass research in community ecology. However, no consistent conclusion exists regarding the response of aboveground biomass to climate warming [?, ?]. Previous findings can be loosely divided into four categories: aboveground biomass increases with temperature [?, ?, ?], decreases with temperature [?, ?, ?], initially increases but then decreases with temperature [?, ?], or does not change with temperature [?, ?, ?].

The response of aboveground biomass to climate warming also varies among different plant functional groups [?, ?, ?, ?]. Studies on alpine meadows have shown that aboveground biomass of grasses and sedges increases after warming, while that of weeds decreases [?, ?]. However, other studies have found that aboveground biomass of grasses and sedges decreases under warming conditions, and weeds become the dominant species in the community [?, ?]. Since the effect of temperature on aboveground biomass of different functional plant groups remains unclear, it is necessary to explore how biomass of different plant functional types responds to simulated warming to understand plant community productivity responses under climate warming and to accurately evaluate ecosystem productivity [?, ?, ?].

Species diversity, an important component of biodiversity research, plays a vital role in maintaining the stability of Earth' s ecosystems and providing ecosystem services [?, ?]. Exploring variation trends in species diversity in the context of climate warming is of great scientific significance for evaluating changes and succession in plant community structure. The response of species diversity to warming is highly time-dependent, with studies showing that different warming durations have different impacts on species diversity [?, ?]. Species diversity was not sensitive to warming in a three-year simulated warming experiment in an alpine meadow [?, ?], whereas five years of simulated warming reduced species diversity [?, ?], and 16 years of warming increased species diversity slightly [?, ?]. Zhao et al. (2003) found that species diversity increased in the first two years of warming but decreased in the third year due to reduced soil moisture. Hydrothermal environmental factors changed under warming treatment, affecting soil nutrient content [?, ?] and making the relationship between environmental factors and species diversity more complex. The relationships between environmental factors and species diversity under warming treatment have been little studied, and the mechanisms remain to be further explored [?, ?].

Terrestrial ecosystems are significant for maintaining the stability and productivity of grassland ecosystems [?, ?]. The Qinghai-Tibet Plateau (QTP) of China is an ecologically fragile zone sensitive to global climate warming and constitutes an ideal region for studying response mechanisms of terrestrial ecosystems to climate warming [?, ?, ?]. Vegetation on the QTP is very sensitive to climate warming [?, ?]. Alpine meadows, a typical vegetation type on the QTP, are a unique result of adaptation to plateau uplift and long-term low-temperature environment formation. They comprise typical plateau zonal and mountainous vertical zonal vegetation, and their ecosystems are extremely fragile and sensitive to climate change and human activity impacts [?, ?]. Alpine meadows developed in the permafrost regions of the QTP, and melting frozen soil can significantly affect meadow plant growth and development under climate warming, thus changing meadow community structure and biomass characteristics [?, ?]. As the climate gets warmer, alpine meadows have shown significant degradation trends, particularly under human disturbance [?, ?], with both biomass and diversity declining. Therefore, assessing the impact of climate warming on alpine meadow ecosystems is important for conserving species diversity and rationally utilizing grasslands on the QTP.

Given the uncertainty in biomass and species diversity responses to increased temperature, we used infrared radiators as warming devices to simulate warming over eight years in this study. We selected an alpine meadow on the QTP as our research object and divided vegetation into three categories: grasses, sedges, and weeds. We analyzed dynamic changes in aboveground biomass and species diversity at different time scales, including the early warming stage (2011-2013) and the late warming stage (2016-2018), to further interpret warming effects on: (1) environmental factors of alpine meadows; (2) species diversity and aboveground biomass of alpine meadows; and (3) relationships between soil hydrothermal factors and species diversity and aboveground biomass. Our findings are expected to provide theoretical support for protecting and rationally using alpine vegetation in high-altitude areas by elucidating responses of aboveground biomass and species diversity to short-term and long-term warming.

2.1 Study Area

The study area is located at the Beiluhe Permafrost Field Station of the Chinese Academy of Sciences (34°49 34 -34°49 37 N, 92°55 57 -92°56 06 E; 4633.5 m a.s.l.; Fig. 1a [Figure 1: see original paper]) on the QTP, China. The site is in an arid and cold area with an annual mean temperature of -5.9°C, mean annual precipitation of 267.6 mm, and mean annual potential evaporation of 1316.9 mm. Located in the permafrost region, it freezes from September to April, and the growing season is from May to September. The vegetation at this site is alpine meadow. During the growing season, the alpine meadow has a vegetation coverage of 83% and is dominated by Cyperaceae and Compositae, with some Leguminosae also present. Kobresia pygmaea (Cyperaceae) is the constructive species, accompanied by Carex moorcroftii (Cyperaceae), Oxytropis pusilla (Leguminosae), Androsace tapete (Primulaceae), Leontopodium nanum (Compositae), and Saussurea pulchra (Compositae). Polygonum viviparum (Polygonaceae) is also common at the study site [?, ?, ?, ?, ?].

2.2 Experimental Design

The experimental plot is located in a typical alpine meadow area about 300 m from the Beiluhe Permafrost Field Station of the Chinese Academy of Sciences. The terrain is relatively flat, vegetation is well-distributed, and the area is not disturbed by grazing or pikas. The experiment was designed as a randomized block with five blocks, each containing two treatments: control and warming (150 W/m^2; Fig. 1b). There were 10 plots total (2 m$×$2 m each), with distances of 4-5 m between adjacent plots [?, ?, ?, ?]. Control plots received no warming treatment and maintained the natural vegetation state. In warming plots, infrared radiators (Kalglo Electronics, Bethlehem, PA, USA) were used as warming devices to simulate warming. The lamp body is a triangular prism measuring 165 cm long and 15 cm wide, and the lamp tube is a cylinder 150 cm long with an 8 mm diameter. The radiator' s reflector surface was suspended 1.5 m above the warming plots, and each group' s outer circumference was surrounded by wire mesh to prevent damage.

2.3 Measurements of Temperature and Moisture

The warming treatment lasted for eight years (from July 2010 to October 2018), with uninterrupted warming applied throughout the entire year. Due to missing data for 2013, 2014, and 2015, we selected temperature and moisture data from 2011, 2012, 2016, 2017, and 2018 for analysis. Air temperature and relative humidity were assessed at 20 cm above the land surface, soil temperature at 5 cm depth, and soil moisture at 10 cm depth. Air temperature and relative humidity were measured using an HMP45C temperature and humidity sensor placed inside a radiation shield to avoid influence from upstream and downstream radiation. Soil temperature was measured with a 109 SS-L temperature sensor and soil moisture with an Envior SMART moisture sensor. All sensors were connected to a CR1000 data collector that recorded average data every 10 min for analysis. All sensors and the data collector were produced by Campbell Scientific Inc., Logan, USA.

2.4 Measurements of Plant Characteristics

Plant characteristics were investigated in early September in 2011, 2012, 2013, 2016, 2017, and 2018. As no vegetation data were collected in 2014 and 2015, the data were divided into two stages on a three-year scale: the early experimental stage (2011–2013) and the late experimental stage (2016–2018). We recorded species name, height, coverage, frequency, abundance, and aboveground biomass. Plant characteristics were measured using an aluminum frame (27 cm$×27cm)dividedinto100gridsbywiremesh, witheachgridmeasuring2.5cm×$2.5 cm. After determining characteristics of each species in the frame, we calculated species diversity indices using these values. We then selected temporary plots around the experimental plots (control and warming) with consistent plant height and coverage. Aboveground biomass from temporary plots was harvested, transported to the laboratory, oven-dried for 24 h at 75°C to constant weight, and weighed. Finally, we established a stepwise regression equation using height, coverage, and aboveground biomass from temporary plots to indirectly obtain aboveground biomass in experimental plots.

2.5 Data Analysis

This study used five years of environmental data (2011, 2012, 2016, 2017, and 2018) and six years of plant data (2011, 2012, 2013, 2016, 2017, and 2018) for multivariate analysis of variance, and five years of environmental and plant data (2011, 2012, 2016, 2017, and 2018) for correlation analysis. Plant data processing included calculations of aboveground biomass, importance value, and species diversity.

First, because the warming experiment was designed for the long term, we selected 100 temporary plots with similar plant height and coverage around experimental plots to estimate aboveground biomass on experimental plots [?, ?]. Plant aboveground biomass data were calculated by establishing a stepwise regression equation among plant height, coverage, and aboveground biomass in SPSS 19.0 software (IBM Corp., Armonk, USA).

AGB308.2622.764121.801ch

(R^2=0.737; P<0.001; n=100), (1)

where AGB is plant aboveground biomass (g/m^2), c is plant coverage (fractional representation), h is plant height (cm), and n is the total number of temporary plots.

Second, by referring to scientific names and taxonomic information in Flora of China (http://www.iplant.cn/foc/), we classified all plant species into three types according to plant functional types: grasses (Gramineae species), sedges (Cyperaceae species), and weeds (except for Gramineae and Cyperaceae species) [?, ?, ?]. We calculated the importance value of plant species according to height, density, coverage, and frequency of each species in each plant functional type to indicate its position and function in the plant community. We focused on plants in the same habitat and thus calculated α-diversity indices, including the Margalef index, Simpson index, Shannon-Weiner index, and Pielou index [?, ?]. These indices were calculated using the following formulas [?, ?] in Microsoft Office Excel 2016.

RHRDRCRFIV,4

21’ 1,SiiHP

1ln(),SiiiHPP

,ln()HES

,RS

where IV is importance value, RH is relative height, RD is relative density, RC is relative coverage, RF is relative frequency, H’ is the Simpson index, S is total number of plant species in each plot, i is plant species, Pi is relative importance value of species i in each plot, H is the Shannon-Weiner index, E is the Pielou index, and R is the Margalef index.

Finally, we used the General Linear Model in SPSS 23.0 (IBM Corp., Armonk, USA) for multi-way analysis of variance to: (1) analyze air temperature, relative humidity, soil temperature, and soil moisture among different treatments, years, and months; (2) analyze plant height, frequency, coverage, density, importance value, and aboveground biomass among different treatments, years, and families;

and (3) analyze species diversity indices between different years and treatments. Bivariate correlation in SPSS 23.0 was used to analyze correlations between soil microclimate (soil temperature and soil moisture) and species diversity and aboveground biomass. Using OriginPro 9.1 software (OriginLab Corp., Hampton, MA, USA), we drew line graphs and column graphs to analyze variations in environmental factors and plant communities under different treatments and years.

3.1.1 Air Temperature and Relative Humidity

In the growing season, air temperature varied significantly among years ($P<0.01$; Table 1). In warming plots, air temperature increased by 0.31°C from 2011 to 2012 and by 0.12°C from 2016 to 2018. Simulated warming increased air temperature by 0.19°C over eight years (2011-2018), with the warming effect showing a significant yearly downward trend. Air temperature also varied significantly by month ($P<0.01$), with temperatures in July and August significantly higher than other months (Fig. 2 [Figure 2: see original paper]). Differences in air temperature among treatments were not significant ($P=0.054$) but reached significance in the treatment × year interaction ($P=0.038$).

In the growing season, variations in relative humidity under different treatments and years reached significant levels ($P=0.037$ and $P=0.016$, respectively; Table 1). In warming plots, relative humidity decreased by 2.54% from 2011 to 2012 and increased by 4.20% from 2016 to 2018. Relative humidity increased by 1.47% on average over eight years (2011-2018). It increased significantly with year and also varied significantly among months ($P<0.01$), particularly with May relative humidity significantly lower than other months (Fig. 2).

Overall, air temperature and relative humidity varied little among treatments in the growing season. In the early warming stage (2011-2013), air temperature increased and relative humidity decreased, making the air warmer and drier. In the late warming stage (2016-2018), both air temperature and relative humidity increased, making the air warmer and wetter. Over eight years of warming, the air generally tended to become warmer and wetter.

3.1.2 Soil Temperature and Soil Moisture

In the growing season, soil temperature differed significantly among treatments ($P<0.01$; Table 2). Warming increased surface soil temperature by 2.44°C in the early stage and 1.30°C in the late stage. Eight years of warming increased surface soil temperature by 1.76°C, with the warming effect decreasing significantly year by year. Soil temperature also varied significantly among months ($P<0.01$), with July and August soil temperatures significantly higher than other months (Fig. 3 [Figure 3: see original paper]).

In the growing season, warming decreased soil moisture by 12.47% in the early stage and 8.08% in the late stage. Eight years of warming decreased soil moisture by 9.90%, with soil moisture decreasing yearly. In terms of months, soil moisture differed significantly among months (P=0.015; Table 2), with August and September soil moisture contents significantly higher than other months (Fig. 3).

Overall, warming led to soil water evaporation, tending to make the soil environment warmer and drier. In the early warming stage, the increase in soil temperature was relatively small while the decrease in soil moisture was relatively large, aggravating soil environment drought. In the late warming stage, soil temperature increased greatly while the decrease in soil moisture was relatively small, alleviating soil environment drought.

3.2 Species Diversity

We identified 39 plant species in the experimental plots, belonging to 11 families and 22 genera. We divided them into three categories by functional type: grasses (seven species belonging to six genera of Gramineae), sedges (six species belonging to two genera of Cyperaceae), and weeds (26 species belonging to 14 genera of nine families). The weed families were Asteraceae, Leguminosae, Polygonaceae, Rosaceae, Cruciferae, Primulaceae, Ranunculaceae, Scrophulariaceae, and Saxifragaceae.

Under warming treatment, importance values of grasses and sedges decreased by 47.56% and 3.67%, respectively, while weeds' importance value increased by 1.37%. However, these changes did not reach significant levels among treatments ($P>0.05$; Table 3). Significant differences in importance value were found between years and families ($P<0.01$), and changes under their combined action were also significant ($P<0.05$). From 2011 to 2013, warming decreased importance values of grasses and sedges by 56.56% and 9.87%, respectively, while increasing weeds' importance value by 1.57%. From 2016 to 2018, grasses' importance value decreased by 35.69%, while sedges' and weeds' importance values increased by 5.21% and 1.08%, respectively (Fig. 4 [Figure 4: see original paper]).

Species diversity indices showed no significant difference among treatments (Table 3). From 2011 to 2013, warming increased the Simpson, Shannon-Wiener, Pielou, and Margalef indices by 5.69%, 8.43%, 3.71%, and 5.26%, respectively. From 2016 to 2018, warming decreased the Simpson, Shannon-Wiener, and Pielou indices by 3.94%, 3.05%, and 4.48%, respectively, while the Margalef index did not change. Over eight years of warming, the Simpson, Shannon-Wiener, and Margalef indices increased by 0.66%, 2.22%, and 2.27%, respectively (Fig. 5 [Figure 5: see original paper]), with these three diversity indices differing significantly among years ($P<0.05$). The Pielou index decreased by 0.40% under eight years of warming, with no significant difference among years (P=0.177).

Overall, during the warming period, grasses' importance value decreased while weeds' increased, indicating that warming did not create an environment conducive to grass growth, and this vegetation type might ultimately be replaced by weeds. Species diversity indices increased in the early warming stage and decreased in the late stage, indicating that long-term warming reduced species diversity, but differences were not significant among treatments.

3.3 Aboveground Biomass

Under warming treatment, aboveground biomass of grasses decreased by 36.55%, while those of sedges and weeds increased by 8.09% and 15.24%, respectively, and total aboveground biomass increased by 13.61% (Fig. 6 [Figure 6: see original paper]). Aboveground biomass differed significantly among families (P<0.01) but did not reach significant levels between treatments (P>0.05; Table 3). From 2011 to 2013, grass aboveground biomass decreased by 52.9%, while sedges and weeds increased by 4.59% and 12.85%, respectively, and total aboveground biomass increased by 17.17%. From 2016 to 2018, grass aboveground biomass decreased by 19.00%, while sedges and weeds increased by 11.09% and 17.30%, respectively, and total aboveground biomass increased by 11.40%. Aboveground biomass changed with year, but differences were not significant (P=0.164; Table 3).

Overall, warming increased aboveground biomass in experimental plots. During the warming period, aboveground biomasses of sedges and weeds increased, while grass aboveground biomass decreased significantly, indicating that warming changed biomass distribution in alpine meadows and thus altered community structure.

3.4 Correlation Analysis of Soil Microclimate with Species Diversity and Aboveground Biomass

We conducted correlation analysis of soil microclimate factors (soil temperature and soil moisture) with species diversity indices and aboveground biomass under short-term and long-term warming conditions (Table 4). No significant correlation existed between species diversity indices and soil microclimate factors under either short-term or long-term warming, with relationships mainly affected by time factors. In the early warming stage, correlations were not significant. At the eight-year warming timescale, soil temperature was positively correlated with the Shannon-Weiner index (r=0.385, P=0.043) and Margalef index (r=0.481, P=0.027), but soil moisture was negatively correlated with the Shannon-Weiner index (r=0.417, P=0.027) and Margalef index (r=0.414, P=0.029).

Under warming conditions, soil temperature had a significant correlation with aboveground biomass. Soil temperature and aboveground biomass were positively correlated in control plots (r=0.660, P=0.014) but negatively correlated in warming plots, especially under long-term warming (r=-0.464, P=0.013). Short-term and long-term warming typically had different effects on relationships between soil microclimate and plants. Overall, no correlation existed between soil microclimate factors and species diversity indices under warming conditions. Aboveground biomass was significantly related to soil temperature, with aboveground biomass decreasing as soil temperature increased.

4.1 Effects of Warming on the Microclimate

Infrared radiators are ideal devices for simulating warming. They can realistically simulate warming mechanisms and daily variation in global climate warming with minimal physical interference to vegetation and soil [**?**, **?**]. Infrared radiators achieve uniform and controllable heating effects, particularly for low-canopy vegetation [**?**, **?**].

Our results showed that eight years of warming increased air temperature by 0.19°C and relative humidity by 1.47%, making the air warmer and wetter overall. According to Wu et al. (2005), data from 77 meteorological stations on the Tibetan Plateau showed that main climate change trends included increased temperature and precipitation, with most areas tending to change from dry to wet. However, controversy remains regarding whether infrared radiators can increase air temperature [**?**, **?**]. In this study, air temperature increased by only 0.19°C after eight years of warming, a relatively small increase that may relate to ecosystem type and other environmental factors such as wind speed [**?**, **?**]. The increase in relative humidity may relate to surface evapotranspiration. Wan et al. (2002) suggested that infrared radiators could directly heat vegetation canopy and soil, thereby increasing plant and soil evaporation and decreasing soil moisture. In their test, soil moisture decreased by 8.74%. Shi et al. (2008) used an open top chamber (OTC) to simulate warming and found that OTC warming directly decreased soil moisture. This indicated that both active warming by infrared radiator and passive warming by OTC decreased shallow soil moisture, causing the soil environment to become warmer and drier.

4.2 Effects of Warming on the Plant Community

We studied effects of short-term and long-term warming on different plant families in two stages: early warming (2011–2013) and late warming (2016–2018). Due to complexity of the alpine meadow ecosystem, different plants have different temperature sensitivities, making it difficult to accurately assess ecosystem responses and adaptation to climate change under short-term warming. Plants and their communities have lagging responses to long-term effects of resource feedback, growth, and competition. Long-term warming responses may be limited by environmental factors such as water and nutrients, making long-term and short-term plant or plant community responses to warming different [**?**, **?**].

Climate change, the primary natural factor affecting biodiversity, determines species distribution and vegetation types. Changes in climate factors lead to variations in species diversity [**?**, **?**]. Our study found species diversity in warming plots was higher than in control plots from 2011 to 2013, while control plot diversity was higher than warming plot diversity from 2016 to 2018. Zhao et al. (2003) found species diversity increased in the first two years of warming but decreased in the third year. Li et al. (2004) found species diversity in a Kobresia humilis meadow decreased after five years of warming compared with control plots. After eight years of warming, our study found species diversity indices changed little, particularly the Margalef index, with no significant difference between treatments. Yang et al. (2017) also revealed in an eight-year warming experiment that species diversity fluctuated within a relatively small range regardless of nighttime or daytime warming. This shows that eight-year warming effects on species diversity are still small, and a significant response may require a longer timescale. Results from a 14-year warming experiment showed species diversity decreased in the 8th year, mainly due to negative competition between invasive and dominant species, indicating that long-term warming could alter grassland community structure [**?**, **?**].

In the context of global climate warming, some species in any plant community are always more sensitive to temperature increases than others, altering interspecific competition and causing changes in dominant species and

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.