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Increased precipitation has stronger effects on plant production of an alpine meadow than does experimental warming in the Northern Tibetan Plateau

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ABSTRACT

The Tibetan Plateau is overall getting warmer and wetter, whereas the relative responses of plant growth to warming and increased precipitation are not fully understood. Therefore, a field warming (control, low- and high-level) and increased precipitation (control, low- and high-level) experiment was conducted to compare the relative effects of warming and increased precipitation on the normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), aboveground biomass (AGB) and gross primary production (GPP) in an alpine meadow in the Northern Tibetan Plateau since June 2014. The low- and high-level experimental warming significantly decreased soil moisture (SM) by 0.02 $m^3 m^{-3}$ and 0.04 $m^3 m^{-3}$, but significantly increased air temperature (T_a) by 1.91 °C and 3.51 °C, respectively, across the three growing seasons in 2014–2016. The low- and high-level warming did not significantly affect NDVI, SAVI, AGB and GPP across the three growing seasons in 2014–2016. The low- and high-level increased precipitation did not significantly affect T_a, but significantly increased SM by 0.02 $m^3 m^{-3}$ and 0.03 $m^3 m^{-3}$, respectively, across the three growing seasons in 2014–2016. The high-level increased precipitation significantly increased NDVI by 18.7%, SAVI by 18.4%, AGB by 11.4% and GPP by 25.0%, whereas the low-level increased precipitation only tended to increase NDVI by 9.8%, SAVI by 8.2%, AGB by 6.2% and GPP by 12.9%. Therefore, increased precipitation had stronger effects on NDVI, SAVI, AGB and GPP than did experimental warming in this alpine meadow site of the Northern Tibetan Plateau.

1. Introduction

Global surface temperature will increase by 1.0–3.7 °C at the end of 21 century (IPCC, 2013) and global annual precipitation increases by 2% since 2000 (Hulme et al., 1998). The Tibetan Plateau is overall getting warmer and wetter (Diffenbaugh and Field, 2013; Lu and Liu, 2010). The warming magnitude on the Tibetan Plateau is much greater than the global average and increases with increasing elevation (Kuang and Jiao, 2016; Yao et al., 2000). Precipitation has increased by 0.67 mm a^{-1} during 1961–2010 on the Tibetan Plateau (Li et al., 2016) and will continue to increase in the 21 century (Ji and Kang, 2013). Many warming and/or increased precipitation experiments have been conducted to quantify responses of alpine ecosystems to the warming and wetting trends on this Plateau (Ganjurjav et al., 2016; Klein et al., 2007; Li et al., 2011; Liu et al., 2011; Shi et al., 2012; Wang et al., 2012; Xu et al., 2010; Xue et al., 2015). However, warming and increased precipitation experiments are fewer than warming experiments or increased precipitation experiments (Dorji et al., 2013; Heng et al., 2011). The responses of alpine ecosystems to warming or increased precipitation can most likely overestimate or underestimate those to warming and increased precipitation. For example, the main effect of experimental warming and interactive effect of experimental warming and increased precipitation on temperature sensitivity of soil respiration was not significant, whereas increased precipitation increased significantly temperature sensitivity of soil respiration in an alpine meadow of the Northern Tibetan Plateau (Shen et al., 2015). Therefore, more in situ warming and increased precipitation experiments are needed to better understand the effects of climatic changes on alpine ecosystems on the Tibetan Plateau (Shen et al., 2014).

There are various alpine ecosystems, including forests, shrublands, alpine meadows and alpine steppes, on the Tibetan Plateau. These alpine ecosystems are representative terrestrial ecosystems in alpine regions at both Asian and global scales. The alpine meadow on the Tibetan Plateau is one of the most typical vegetation types and one of the most sensitive grassland types to climatic change (Zhao et al., 2012). There are only a few warming and increased precipitation studies in alpine meadows on the Tibetan Plateau, and these studies mainly focus on the responses of soil carbon, nitrogen, respiration and

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plant phenology (Dorji et al., 2013; Heng et al., 2011; Shen et al., 2015). Normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), aboveground biomass (AGB) and gross primary production (GPP) are four vital indicators of plant production. They are important components of global carbon cycling. However, to our knowledge, no studies have reported their responses to warming and increased precipitation in alpine meadows under controlled warming and increased precipitation conditions on the Tibetan Plateau. On the other hand, several previous studies have analyzed the relationships between satellite-based vegetation indices and climatic variables (e.g. air temperature and precipitation) (Chu et al., 2007; Sun et al., 2013) or the effects of climatic change on ground-based AGB along an environmental (e.g. precipitation or elevation) gradient (Wang et al., 2013; Wu et al., 2014). However, satellite-based vegetation indices are simultaneously affected by climatic change and human activities (e.g. grazing). Grazing can alter warming effects on plant production in alpine grasslands on the Tibetan Plateau (Klein et al., 2007; Wang et al., 2012). Along an environmental gradient, not only climatic variables but also vegetation types and soil characteristics (e.g. soil nitrogen availability) most likely change. Changes in vegetation types and soil characteristics can disturb the effects of climatic variables on plant production (Ganjurjav et al., 2016; Wang et al., 2013). In situ warming and increased precipitation experiments can minimize these disturbed factors mentioned above (Rustad et al., 2001). Third, several previous studies have indicated that precipitation rather than air temperature predominate variations of satellite-based vegetation indices on the Tibetan Plateau (Chu et al., 2007; Sun et al., 2013), no studies have focused on the relative responses of plant production to warming and increased precipitation under controlled warming and increased precipitation conditions. Distinguishing the relative strengths of warming and increased precipitation on plant production plays an vital effect on grassland use management and livestock husbandry sustainable development under future climatic change. Therefore, it remains unclear how climatic warming and increased precipitation will influence plant production in alpine meadows on the Tibetan Plateau. More in situ warming and increased precipitation experiments under controlled warming and increased precipitation conditions are needed to investigate their relative effects of warming and increased precipitation on plant production in alpine meadows on the Tibetan Plateau.

In this study, an in-situ warming and increased precipitation experiment was conducted in an alpine meadow of the Northern Tibetan Plateau. The main objectives of this study were to (1) examine the effects of experimental warming and increased precipitation on NDVI, SAVI, AGB and GPP; and (2) investigate whether increased precipitation had stronger effects on NDVI, SAVI, AGB and GPP than did experimental warming.

2. Materials and methods

2.1. Study area and experimental design

The study area (30°30′N, 91°04′E) was located at the Damxung Grassland Observation Station, Tibet Autonomous Region of China. Detailed description on climatic, soil and vegetation characteristics are given in our previous studies (Shen et al., 2015).

The field experiment was based on a complete factorial design with three replicates of nine treatments: control (C), low-level experimental warming (LW), high-level experimental warming (HW), low-level increased precipitation (LP), low-level experimental warming plus low-level increased precipitation (LW + LP), high-level experimental warming plus low-level increased precipitation (HW + LP), high-level increased precipitation (HP), low-level experimental warming plus high-level increased precipitation (LW + HP), and high-level experimental warming plus high-level increased precipitation (HW + HP). There were a total of 27 experimental plots. Two heights (40 cm and 80 cm) of open top chambers (OTC), which were hexagonal in shape with 60° inwardly inclined sides, were installed to obtain the two magnitudes of warming in early June 2014. All the top opening of the two heights of OTCs was 60 cm and left in place year round. These OTCs were similar with those of (Li et al., 2011). Two diameters (approximately 44 cm and 62 cm) of precipitation collection funnels with rubber tubing (2 cm inner diameter) were installed to obtain the two magnitudes (15% and 30%) of increased precipitation in early June 2014. These increased precipitation devices were similar with those of some previous studies (Blankinship et al., 2010; Ma et al., 2012). The increased magnitudes of precipitation was comparable to previous studies (i.e. 6–50%) (Chimner et al., 2010; Huang et al., 2015; Niu et al., 2008; Shen et al., 2015) and the predicted values in the 21 century (10–25%) (Ji and Kang, 2013).

Table 1
Repeated-measures analysis of variance was used to estimate the main and interactive effects of experimental warming (W), increased precipitation (IP), measuring year (Y) and month (M) on the normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), aboveground biomass (AGB) and gross primary production (GPP).

Model	NDVI	SAVI	AGB	GPP
W	1.96	1.77	1.97	1.72
IP	4.19*	2.85	3.85*	6.32**
Y	79.84***	70.42***	62.16***	107.47***
M	165.51***	78.29***	126.09***	319.67***
W × IP	0.15	0.27	0.14	0.23
W × Y	2.92*	3.53*	3.56*	1.54
W × M	1.35	1.89	1.37	2.76*
IP × Y	0.74	1.04	0.90	0.67
IP × M	0.50	0.84	0.15	0.39
Y × M	31.94***	50.98***	20.06***	73.89***
W × IP × Y	0.43	0.29	0.43	0.66
W × IP × M	0.19	0.33	0.19	0.40
W × Y × M	0.72	0.95	0.73	0.58
IP × Y × M	0.42	0.31	0.38	0.55
W × IP × Y × M	0.24	0.29	0.24	0.36

*, ** and *** indicates significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

2.2. Microclimate measurements

Meteorological stations (HOBO weather station, Onset Computer, Bourne, MA, USA) continuously auto-monitored soil moisture at a depth of 0.10 m (SM), air temperature (T_a) and relative humidity (RH) at a height of 0.15 m during growing season (June–September) in 2014–2016. Measured T_a and RH was used to calculate vapor pressure deficit (VPD). Growing season accumulated temperature (AccT) was the sum of ≥5 °C daily air temperature during June–September. Growing season precipitation (GSP) was obtained from the Damxung County meteorological station. The ratio of GSP to AccT (GSP/AccT) was used as a synthesized factor of air temperature and precipitation (Wang et al., 2013).

2.3. NDVI, SAVI, AGB and GPP

During the growing season in 2014–2016, photographs in a 0.50 m × 0.50 m subplot in the center of each plot were taken by a Tetracam Agricultural Digital Camera (ADC, Tetracam Inc., Chatsworth, CA, USA). NDVI and SAVI values were obtained from these photographs using a PixelWrench2 software (Liu et al., 2012; Yi et al., 2011).

A non-destructive method was used to estimate aboveground biomass (AGB). That is, NDVI data were used to estimate AGB ($AGB = 10.33e^{3.28NDVI}$) (Fu and Shen, 2016). Moderate Resolution Imaging Spectroradiometer (MODIS) GPP algorithm was used to estimate GPP. The MODIS GPP algorithm was validated by our previous study (Fu et al., 2017) which conducted in the same alpine meadow as this study. Detailed descriptions on the MODIS GPP algorithm are given in previous studies (Fu et al., 2017).