Clipping Alters the Response of Biomass Production to Experimental Warming: A Case Study in an Alpine Meadow on the Tibetan Plateau, China

FU Gang^{1 a} <http://orcid.org/0000-0002-6055-8730>; e-mail: fugang09@126.com

SUN Wei^{1 a} <http://orcid.org/0000-0001-5591-4799>; e-mail: wsun@igsnr.ac.cn

YU Cheng-Qun¹ <http://orcid.org/0000-0002-4044-105X>; e-mail: yucq@igsnr.ac.cn

ZHANG Xian-Zhou¹ <http://orcid.org/0000-0003-2643-7430>; e-mail: zhangxz@igsnr.ac.cn

SHEN Zhen-Xi¹ <http://orcid.org/0000-0002-3485-5459>; e-mail: shenzx@igsnr.ac.cn

LI Yun-Long^{1,2} <http://orcid.org/0000-0002-2203-6843>; e-mail: liyunlongwf@163.com

YANG Peng-Wan^{1,2} <http://orcid.org/0000-0003-1045-5714>; e-mail: yangpengwan2012@126.com

ZHOU Nan^{1,2} <http://orcid.org/0000-0002-9816-2678>; e-mail: zhoun.13s@igsnr.ac.cn

^a The author contributed equally to this work

¹ Lhasa Plateau Ecosystem Research Station, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

² University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract: Predicting how human activity will influence the response of alpine grasslands to future warming has many uncertainties. In this study, a field experiment with controlled warming and clipping was conducted in an alpine meadow at three elevations (4313 m, 4513 m and 4693 m) in Northern Tibet to test the hypothesis that clipping would alter warming effect on biomass production. Open top chambers (OTCs) were used to increase temperature since July, 2008 and the OTCs increased air temperature by approximately 0.9°C ~ 1.8°C during the growing in 2012. Clipping was conducted three times one year during growing season and the aboveground parts of all live plants were clipped to approximately 0.01 m in height using scissors since 2009. Gross primary production (GPP) was calculated from the Moderate-

Resolution Imaging Spectroradiometer GPP algorithm and aboveground plant production was estimated using the surface-measured normalized difference vegetation index in 2012. Warming decreased the GPP, aboveground biomass (AGB) and aboveground net primary production (ANPP) at all three elevations when clipping was not applied. In contrast, warming increased AGB at all three elevations, GPP at the two lower elevations and ANPP at the two higher elevations when clipping was applied. These findings show that clipping reduced the negative effect of warming on GPP, AGB and ANPP, suggesting that clipping may reduce the effect of climate warming on GPP, AGB and ANPP in alpine meadows on the Tibetan Plateau, and therefore, may be a viable strategy for mitigating the effects of climate change on grazing and animal husbandry on the Tibetan Plateau.

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Introduction

Alpine ecosystems generally accumulate large amounts of carbon (C) under their low temperature conditions (Ni 2002; Moriyama et al. 2013), making them highly sensitive to climate change (Fu et al. 2012b; Zhao et al. 2012). The Tibetan Plateau, sometimes known as “the Third Pole of the Earth”, covers ~2.5 million km² and about one-third of this area is alpine meadows, which are vital pasturelands (Cao et al. 2004; Fu et al. 2012c; Shen et al. 2014). The global surface temperature is predicted to increase by 1.0°C ~ 3.7°C by the end of this century and the Tibetan Plateau is one of the most sensitive regions to climatic change (IPCC 2013; Fu et al. 2015). Therefore, it is very important to understand how climatic warming and human activity affects C cycling in the alpine meadows of the Tibetan Plateau.

Gross primary production (GPP), aboveground biomass (AGB) and aboveground net primary production (ANPP) are three primary components of the C cycle in the alpine meadow ecosystem, which is a system highly sensitive to climatic change that could also have significant feedbacks to global climate change (Yang et al. 2009; Fu et al. 2012a). Understanding the responses of this system to warming and clipping is crucial for predicting changes in C cycling with global climate change. However, the responses of GPP, AGB and ANPP to warming (De Boeck et al. 2007; Wu et al. 2011; Jiang et al. 2012; Wang et al. 2012, 2013) and clipping (Wan and Luo 2003; Klein et al. 2007) have been inconsistent with respect to vegetation types and initial climatic conditions.

Although several warming experiments have been performed in alpine meadows on the Tibetan Plateau, the responses of plant biomass/productivity to warming have been inconsistent (Klein et al. 2007; Wang et al. 2012; Fu et al. 2013b). The different responses of plant productivity to warming could be related to different warming patterns (Wang et al. 2012). However, Klein et al. (2007) and Wang et al. (2012) showed contradictory results for the response of

ANPP to grazing in the same alpine meadow with a mean elevation of 3200 m on the Tibetan Plateau. This was probably attributable to the different grazing patterns and intensities present on this meadow. Only one previous study has investigated the response of GPP to warming in alpine meadows along an elevation gradient on the Tibetan Plateau (Fu et al. 2013b) and no previous studies have described the response of GPP to clipping in this situation, especially in elevation gradients >4300 m. Therefore, how climate change affects plant productivity and how clipping influences the warming effects on plant productivity in alpine meadows on the Tibetan Plateau remains unclear and requires investigation.

In this study, a controlled warming and clipping experiment was conducted in an alpine meadow at three elevations (4313 m, 4513 m and 4693 m) in Northern Tibet. Previous studies have showed that grazing or clipping decreases the effects of warming on ANPP in an alpine meadow on the Tibetan Plateau (Klein et al. 2007; Wang et al. 2012). Therefore, this study hypothesized that clipping will decrease the response of GPP, AGB and ANPP to warming.

1 Materials and Methods

1.1 Study area

The study area (30°30' – 30°32' N, 91°03' – 91°04' E) was located at the Damxung Grassland Observation Station in the Tibet Autonomous Region of China (Fu et al. 2013a). The mean annual air temperature is 1.3°C and the mean annual precipitation is ~476.8 mm (Fu et al. 2013a). The soil texture is sandy loam and the soil layer is 0.5–0.7 m thick, with 0.3% ~ 11.2% organic matter, 0.03% ~ 0.49% total N and pH 6.0 ~ 6.7 (Fu et al. 2012c). The typical vegetation type in the study area is *Kobresia*-dominated alpine meadow (Fu et al. 2012b).

1.2 Experimental design

The field experiment was set up in three alpine meadow sites located at a low (4313 m), mid (4513 m) and high (4693 m) elevation. The field experiment was based on a complete two-factor

design (warming and clipping) with three replicates of four treatments: no warming and no clipping (NW+NCL), warming and no clipping (W+NCL), clipping and no warming (CL+NW), warming plus clipping (W+CL) at each elevation, making a total of 36 experimental plots. In July 2008, six open top chambers (OTCs) were randomly installed and left in place year round at each elevation to enhance the temperature for the warmed plots (W+NCL and W+CL) (Marion et al. 1997). The OTCs were 1.45 m × 1.00 m × 0.40 m (Fu et al. 2013a; Yu et al. 2014). There was one unwarmed plot in the vicinity of each OTC. Clipping was conducted three times a year (generally in June, July and September) for the two clipped treatments (CL+NW and W+CL) since 2009. All the aboveground parts of live plants were clipped to approximately 0.01 m in height using scissors. All the clipped plant materials were removed, oven-dried at 65°C for 48 h and weighted.

Soil temperature (5 cm, TMB-M006), soil water content (SWC) (10 cm, SMC-M005), air temperature and relative humidity (15 cm, THB-M008) were continuously auto-monitored by data loggers (HOBO weather station, Onset Computer, Bourne, MA, USA). Vapor pressure deficit (VPD) was the difference between saturation and actual vapor pressures, which was calculated using the surface measured air temperature and relative humidity (Fu et al. 2012a). Experimental warming increased daily T_a by 1.08°C, 1.81°C and 0.94°C and increased daily VPD by 0.05, 0.05 and 0.03 kPa at the low, mid and high elevations, respectively from June to September 2012 (Fu et al. 2013b). High VPD can result in stomatal closure and, in turn, affect plant photosynthesis. Warming-induced increases in VPD can aggravate this effect. In contrast, clipping has been found to have no significant effects on these environmental factors (Fu et al. 2013a).

1.3 Normalized difference vegetation index

A Tetracam Agricultural Digital Camera (ADC, Tetracam Inc., Chatsworth, CA, USA) was used to take photographs in a 0.5 m × 0.5 m subplot in the center of each plot from late June to September 2012. The camera has green (520 ~ 600 nm), red (630–690 nm) and near-infrared (760 ~ 900 nm) bands and can produce 2048 × 1536 pixels with an

8.0 mm lens (Fu et al. 2013b). The lens of the ADC was parallel to the ground at a height of ~1.0 m to limit variations in spatial resolution and field of view (Fu et al. 2013b). The field of view and spatial resolution were ~0.8 m × 0.6 m and 0.4 mm, respectively. Calibration photographs of a white Teflon plate provided by the Tetracam manufacturer were taken before and after each batch of the target photographs and when the light condition changed remarkably. All target photographs were processed using PixelWrench2 software (included with the ADC) to obtain the normalized difference vegetation index (NDVI) and the calibration parameters from photographs of the white Teflon calibration plate (Fu et al. 2013b).

1.4 GPP algorithm

The GPP was calculated from the Moderate-Resolution Imaging Spectroradiometer (MODIS) GPP algorithm. The GPP algorithm has been validated by a previous study (Fu et al. 2012a). Moreover, Fu et al. (2013b) quantified the effect of short-term (<3 year) experimental warming on GPP in alpine meadows on the Tibetan Plateau.

The MODIS GPP algorithm is based on a light use efficiency (LUE) approach (Reichstein et al. 2007). Absorbed photosynthetically active radiation (APAR) by the plant canopy and LUE were used to calculate the GPP (g C day⁻¹),

$$GPP = LUE \times APAR \quad (1)$$

LUE is estimated as

$$LUE = LUE_{\max} \times T_{a\min_scalar} \times VPD_scalar \quad (2)$$

where $LUE_{\max}$ refers to the ecosystem apparent quantum yield or maximum light use efficiency (g C MJ⁻¹). The $LUE_{\max}$ was set to be 0.81 g C MJ⁻¹ (Fu et al. 2012a). The two attenuation scalars, $T_{a\min_scalar}$ and VPD_scalar , were calculated using the daily minimum T_a ($T_{a\min}$) and daytime average VPD, respectively (Reichstein et al. 2007).

$$T_{a\min_scalar} = \begin{cases} 0, & T_{a\min} < T_{a\min_min} \\ \frac{T_{a\min} - T_{a\min_min}}{T_{a\min_max} - T_{a\min_min}}, & T_{a\min_min} < T_{a\min} < T_{a\min_max} \\ 1, & T_{a\min} > T_{a\min_max} \end{cases} \quad (3)$$

$$VPD_{\text{—scalar}} = \begin{cases} 0, & VPD > VPD_{\text{max}} \\ \frac{VPD_{\text{max}} - VPD}{VPD_{\text{max}} - VPD_{\text{min}}}, & VPD_{\text{min}} < VPD < VPD_{\text{max}} \\ 1, & VPD < VPD_{\text{min}} \end{cases} \quad (4)$$

APAR was calculated as:

$$APAR = PAR \times FPAR \quad (5)$$

where FPAR was the fraction of plant canopy APAR and was calculated using the observed NDVI values (Fu et al. 2013b).

$$FPAR = \frac{FPAR_{NDVI} + FPAR_{SR}}{2} \quad (6)$$

$$FPAR_{NDVI} = \frac{(NDVI - NDVI_{\text{min}})(FPAR_{\text{max}} - FPAR_{\text{min}})}{NDVI_{\text{max}} - NDVI_{\text{min}}} + FPAR_{\text{min}} \quad (7)$$

$$FPAR_{SR} = \frac{(SR - SR_{\text{min}})(FPAR_{\text{max}} - FPAR_{\text{min}})}{SR_{\text{max}} - SR_{\text{min}}} + FPAR_{\text{min}} \quad (8)$$

$$SR = \frac{1 + NDVI}{1 - NDVI} \quad (9)$$

where $FPAR_{\text{max}} = 0.95$ and $FPAR_{\text{min}} = 0.001$ (Fu et al. 2013b).

Other model parameters to calculate GPP can be found in Fu et al. (2013b).

1.5 AGB and ANPP estimation

AGB and ANPP were estimated using a non-destructive approach (Fu et al. 2013b). Based on the regression equation ($AGB = 10.33e^{3.28NDVI}$, $R^2 = 0.64$, $p < 0.001$, $n = 135$) between AGB and NDVI (Fu et al. 2013b), the AGB was estimated for all treatments and elevations. The maximum AGB during the growing season was treated as the ANPP.

1.6 Statistical analysis

At each site a repeated-measures ANOVA with experimental

warming and clipping as the between subject factors and sampling date as the within subject factor was conducted for GPP and AGB (Table 1). A univariate ANOVA was conducted for ANPP at each elevation. Linear regression analyses between GPP, AGB, ANPP, T_a and SWC were conducted. All the statistical analyses were performed using SPSS software (version 16.0; SPSS Inc., Chicago, IL).

2 Results and Discussion

The GPP and AGB showed similar seasonal dynamics along the three elevations regardless of the warming and clipping treatments (Figure 1). The significant seasonal changes of GPP and AGB (Table 1) were similar to those in previous studies and the average GPP and AGB values (Figure 1) were close to previous observations in alpine meadows on the Tibetan Plateau (Hu et al. 2008; Fu et al. 2013b).

Regardless of clipping effects, warming significantly decreased the average GPP and AGB by 16.0% ($-0.15 \text{ g C m}^{-2} \text{ d}^{-1}$) and 11.3% (-2.95 g m^{-2}), respectively, at the low elevation (Table 1). Warming non-significantly reduced GPP by 2.7% ($-0.04 \text{ g C m}^{-2} \text{ d}^{-1}$) and AGB by 6.2% (-2.17 g m^{-2}) at the mid elevation and reduced GPP by 6.4% ($-0.10 \text{ g C m}^{-2} \text{ d}^{-1}$) and AGB by 2.3% (-0.98 g m^{-2}) at the high elevation irrespective of clipping (Table 1). These results are in line with previous studies which showed that warming significantly or partially reduced GPP and AGB (Fu et al. 2013b).

Table 1 Repeated measures ANOVA indicating *F* values for the main and interactive effects of warming (W), clipping (CL) and measuring date (D) on aboveground biomass (AGB, g m^{-2}) and gross primary production (GPP, $\text{g C m}^{-2} \text{ d}^{-1}$) in an alpine meadow at different elevations in Northern Tibet

Model	AGB			GPP		
	4313 m	4513 m	4693 m	4313 m	4513 m	4693 m
Warming	9.01*	0.91	0.26	12.27**	0.20	2.51
Clipping	37.14***	34.99***	27.84***	40.59***	33.39***	28.51***
Date	58.01***	81.01***	115.01***	187.30***	364.01***	392.03***
W×CL	12.48**	3.25	0.47	14.33**	6.20*	1.52
W×D	3.36	0.71	9.23***	5.04*	1.25	9.37***
CL×D	9.55**	11.92***	10.95***	12.08***	19.52***	15.22***
W×CL×D	1.86	2.06	0.62	2.31	1.63	1.43

Notes: *, ** and *** represent $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively

Figure 1 Seasonal variation of gross primary production (GPP, $\text{g C m}^{-2} \text{d}^{-1}$) and aboveground biomass (AGB, g m^{-2}) under controlled warming and clipping conditions in an alpine meadow at elevations of 4313 m (a, d), 4513 m (b, e) and 4693 m (c, f) in Northern Tibet. Error bars represent standard errors ($n = 3$). NW+NCL: no warming and no clipping, W+NCL: warming and no clipping, CL+NW: clipping and no warming, W+CL: warming and clipping.

In addition, previous studies have found that warming decreased ecosystem respiration and soil microbial biomass in the same alpine meadow, although not all these declines were significant (Fu et al. 2012b, 2013a). These findings imply that warming depressed some fluxes and pools of the C cycle in this alpine meadow. Warming tended to decrease ANPP at the lower elevations, but tended to increase ANPP at the high elevation regardless of clipping. This finding was not in line with previous studies which showed that warming significantly reduced or increased ANPP in an alpine meadow on the Tibetan Plateau (Klein et al. 2007; Wang et al. 2012). These results implied that the response of GPP, AGB and ANPP to warming most likely varied in each alpine meadow on the Tibetan Plateau.

In the same alpine meadow, a previous study implied that the declines of GPP and AGB under warming were simultaneously suppressed by experimental warming-induced soil drying and temperature increase (Fu et al. 2013b). In line with Fu et al. (2013b), this study found that GPP, AGB and ANPP increased with increasing SWC, and decreased with increasing T_a (Figure 2). Moreover, the declines of GPP, AGB and ANPP under warming may be also related to changes in the soil

microbial biomass because soil microbial activity may affect soil nitrogen (N) availability. Plant productivity increases with increasing soil N availability or inorganic N in alpine meadows on the Tibetan Plateau (Rui et al. 2011; Zong et al. 2013; Fu et al. 2014; Yu et al. 2014). Zong et al. (2013) showed that warming significantly reduced the net N mineralization rate at low elevations. Similarly, Yu et al. (2014) found that warming significantly decreased soil inorganic N at low and mid elevations. The reduction in soil N availability may reduce plant photosynthesis and biomass accumulation in the alpine meadows of this study. In addition, the different effects of warming on GPP and AGB may be attributed to different temperature and moisture conditions (Fu et al. 2013b), changes in soil microbial biomass (Fu et al. 2012b) and changes in inorganic N (Yu et al. 2014) at the three elevations. The experimental warming-induced warming and drying might have caused a deviation from the optimum conditions, and the level of this deviation decreased with increasing elevation (Fu et al. 2013b). The experimental warming-induced decrease in soil microbial biomass and inorganic N content also declined with increasing elevation (Fu et al. 2012b; Yu et al. 2014). Experimental warming-induced changes in

Figure 2 Relationships between growing-season average gross primary production (GPP, $\text{g C m}^{-2} \text{d}^{-1}$), aboveground biomass (AGB, g m^{-2}), aboveground net primary production (ANPP, g m^{-2}) and soil water content (SWC, $\text{m}^3 \text{m}^{-3}$) (a, c, e) and between growing-season average GPP, AGB, ANPP and air temperature (T_a , $^{\circ}\text{C}$) (b, d, f) across elevation and warming and clipping treatments in an alpine meadow in Northern Tibet.

GPP, AGB and ANPP tended to increase with that of SWC and T_a (Figure 3).

Regardless of warming effects, clipping significantly reduced GPP by 27.3% ($-0.27 \text{ g C m}^{-2} \text{d}^{-1}$), 30.0% ($-0.53 \text{ g C m}^{-2} \text{d}^{-1}$) and 20.1% ($-0.33 \text{ g C m}^{-2} \text{d}^{-1}$) and AGB by 21.8% (-6.00 g C m^{-2}), 33.2% ($-13.46 \text{ g C m}^{-2}$) and 21.3% ($-10.15 \text{ g C m}^{-2}$) at the low, mid and high elevations, respectively (Table 1, Figure 1). This finding was in line with previous studies (Wan and Luo 2003; Lin et al. 2011). Considering the non-significant changes in temperature and water availability conditions caused by clipping (Fu et al. 2013a), the depression effect of clipping on GPP may be mainly attributed to the effect of FPAR. The removal of plant photosynthesis organs by clipping can explain the decreases of GPP, which, in turn, resulted in AGB reductions. The previous study showed that grazing

Figure 3 Relationships between warming-induced changes in growing-season average gross primary production (GPP, $\text{g C m}^{-2} \text{d}^{-1}$), aboveground biomass (AGB, g m^{-2}), aboveground net primary production (ANPP, g m^{-2}) and soil water content (SWC, $\text{m}^3 \text{m}^{-3}$) (a, c, e) and between warming-induced changes in growing-season average GPP, AGB, ANPP and air temperature (T_a , $^{\circ}\text{C}$) (b, d, f) across elevation and warming and clipping treatments in an alpine meadow in Northern Tibet.

significantly decreased soil inorganic N content at the two lower elevations (Fu et al. 2014) and soil microbial biomass N at the low and high elevations (Fu et al. 2012c). These findings implied that the negative effect of clipping on GPP and AGB may be also attributed to the reduction of soil N availability probably caused by clipping. However, further studies are necessary to further investigate the probable differences between clipping and grazing. The main effects of clipping on ANPP were non-significant at the three elevations. Likewise, Klein et al. (2007) demonstrated that clipping increased ANPP, but these increases were non-significant. Wang et al. (2012) indicated that grazing did not affect ANPP in 2006, 2009 or 2010.

Without clipping, warming significantly decreased GPP by 27% ($-0.31 \text{ g C m}^{-2} \text{d}^{-1}$) and AGB by 20.9% (-6.43 g C m^{-2}) at the low elevation, and

GPP by 10.1% ($-0.17 \text{ g C m}^{-2} \text{ d}^{-1}$) at the high elevation. It also had fractional negative effects on GPP (-14.2% , $-0.27 \text{ g C m}^{-2} \text{ d}^{-1}$) and AGB (-14.4% , -6.28 g C m^{-2}) at the mid elevation and AGB (-4.7% , -2.30 g C m^{-2}) at the high elevation without clipping. In contrast, with clipping, warming non-significantly increased AGB by 2.5% ($+0.52 \text{ g C m}^{-2}$), 7.4% ($+1.93 \text{ g C m}^{-2}$) and 0.9% ($+0.34 \text{ g C m}^{-2}$) at the low, mid and high elevations, respectively, and non-significantly increased GPP at the two lower elevations (low: $+1.7\%$, $+0.01 \text{ g C m}^{-2} \text{ d}^{-1}$; mid: $+16.4\%$, $+0.19 \text{ g C m}^{-2} \text{ d}^{-1}$), but non-significantly reduced GPP at the high elevation by 1.6% ($-0.02 \text{ g C m}^{-2} \text{ d}^{-1}$) with clipping. Warming non-significantly decreased ANPP by 29.89% ($-14.38 \text{ g C m}^{-2}$), 5.96% (-4.45 g C m^{-2}) and 7.16% (-6.09 g C m^{-2}) at the low, mid and high elevation, respectively, without clipping. With clipping, warming non-significantly decreased ANPP by 7.60% (-3.79 g C m^{-2}) at the low elevation, but non-significantly increased ANPP by 5.07% ($+3.32 \text{ g C m}^{-2}$) and 7.23% ($+6.68 \text{ g C m}^{-2}$) at the mid and high elevation, respectively. In addition, there were significant interactive effects of warming and clipping on AGB at the low elevation and GPP at the low and mid elevations (Table 1). These findings suggested that clipping reduced the negative effect of warming on GPP, AGB and ANPP, which was in line with our study hypothesis and results of previous studies (Klein et al. 2007). Similarly, Wang et al. (2012) found that

the positive effect of warming on ANPP was reduced by sheep grazing in an alpine meadow on the Tibetan Plateau. Therefore, clipping or grazing can reduce the effects of warming on plant productivity in alpine meadows on the Tibetan Plateau.

3 Conclusions

Our results show that clipping reduced the negative effect of warming on GPP, AGB and ANPP in an alpine meadow in Northern Tibet. Therefore, clipping may be a viable strategy for mitigating the effects of climate change on grazing and animal husbandry on the Tibetan Plateau.

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