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## Postprint: Investigating Climate Warming Effects on Tibetan Plateau Grassland Ecosystems Using OTCs Simulated Warming

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### Abstract

Open-Top Chamber (OTC) warming experiments constitute one of the primary methods for investigating the relationship between global climate change and terrestrial ecosystems, and have been widely applied in the Tibetan Plateau region. Through a review of recent domestic and international research literature, this paper comprehensively analyzes the responses of Tibetan Plateau grassland ecosystems to OTC simulated warming experiments from the perspectives of plant phenology, community structure, biomass, and soil. The study reveals that warming advances community green-up, delays senescence, and extends the growing season; promotes the growth of Poaceae plants; shifts the underground biomass allocation pattern to deeper soil layers in alpine meadows; and that the response of alpine grassland ecosystems to simulated warming exhibits uncertainty influenced by region, community type, and experimental duration. Under warming conditions, soil moisture changes induced by precipitation and permafrost thaw regulate ecosystem responses to climate warming through pathways controlling phenology, productivity, and soil processes. Based on these findings, several directions for future research are proposed.

### Full Text

#### Effects of Global Warming on Alpine Grassland Ecosystems on the Tibetan Plateau Based on OTCs Warming Experiments

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## Abstract

Open-top chamber (OTC) warming experiments represent one of the primary methods for investigating relationships between global climate change and terrestrial ecosystems and have been widely applied across the Tibetan Plateau. This paper synthesizes recent domestic and international literature to comprehensively analyze Tibetan Plateau grassland ecosystem responses to OTC simulated warming, focusing on plant phenology, community structure, biomass, and soil characteristics. The synthesis reveals that warming advances community green-up dates, delays withering dates, and extends the growing season. Warming benefits gramineous plant growth and shifts belowground biomass allocation patterns to deeper soil layers in alpine meadows. However, responses of alpine grassland ecosystems to simulated warming exhibit uncertainty, influenced by geographic location, community type, and experimental duration. Under warming conditions, soil moisture changes induced by precipitation and permafrost thaw regulate ecosystem responses to climate warming by controlling phenology, productivity, and soil processes. Based on these findings, we propose several priority areas for future research.

**Keywords:** Tibetan Plateau, biomass, community structure, soil, phenology

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## Introduction

According to the Intergovernmental Panel on Climate Change, global average land and sea surface temperatures increased by 0.78°C during 2003–2012 compared to 1900–1950 (IPCC, 2013). Under global warming, high-latitude and high-altitude regions experience greater temperature increases and exhibit heightened sensitivity and more rapid response rates (Imhoff et al., 2004; Xu and Xue, 2013; Walther et al., 2002). Over the past 50 years, warming on the Tibetan Plateau has exceeded twice the global average, reaching 0.3–0.4°C per decade. Permafrost upper boundary temperatures have risen by approximately 0.3°C per decade, while the active layer has thickened at rates of 3.6–7.5 cm · a<sup>-1</sup> (Chen et al., 2015; Liu & Chen, 2000). Alpine grassland ecosystems, covering approximately 70% of the Tibetan Plateau, are extremely fragile and highly sensitive to climate change and human disturbance, making them ideal systems for studying response patterns and mechanisms of alpine grasslands to climate change (Piao et al., 2011; Li et al., 2011a).

In situ warming experiments under natural field conditions represent a primary approach for understanding and predicting mechanisms underlying terrestrial

ecosystem responses to global change (Niu et al., 2007). Open-top chambers (OTCs) constitute the simplest and most widely used warming method (Richardson et al., 2000). Compared to other warming techniques, OTCs minimize soil disturbance while offering low cost, easy replication, and simple operation, making them suitable for long-term field observations (Klein et al., 2004). Consequently, OTCs have been extensively applied across Tibetan Plateau grassland ecosystems, including alpine meadows, alpine steppes, and alpine swamp meadows.

Tibetan Plateau alpine grassland ecosystems represent uniquely distinctive grassland types with significant ecological functions and values for biodiversity conservation, soil and water retention, and ecological balance maintenance (Piao et al., 2011). Global warming has profoundly altered the structure and function of these grassland ecosystems (Klein et al., 2004; Piao et al., 2011). However, studies using OTCs to simulate warming across different grassland ecosystem types have yielded inconsistent conclusions, with some findings even contradicting each other, thereby limiting understanding of dynamic change patterns and driving mechanisms of grassland ecosystem adaptation to global warming. This paper systematically synthesizes recent research findings on Tibetan Plateau grassland ecosystem responses to OTC warming experiments, examining plant and soil responses to climate warming through the lenses of plant phenology, community structure, biomass, and soil characteristics. Our objective is to enhance understanding of response characteristics and evolutionary trends of alpine grassland ecosystems adapting to global warming, providing scientific and theoretical foundations for sustainable management and development of these ecosystems.

### 1.1 Effects of Warming on Plant Phenology

Plant phenology is considered the “fingerprint” of climate warming, exhibiting particularly sensitive responses to temperature increases. Warming advances the onset of all phenological stages in alpine meadow communities while delaying their cessation; bud stage onset and cessation are both delayed, while flowering onset is delayed and flowering cessation advanced, resulting in an average plant population growth period extension of 4.95 days (Zhou et al., 2000).

Alpine grassland ecosystem plants exhibit differential responses across phenological stages and among species (Pau et al., 2011; Richardson et al., 2013; Zhu, 2016; Zhang et al., 2018). Zhu et al. (2016) found that warming altered reproductive timing for most species in northern Tibetan alpine meadow communities, with warming, species identity, and their interactions significantly affecting plant reproductive phenology. Budding and flowering stages showed greater sensitivity to warming than fruiting stages. Different functional groups (early- and late-flowering) responded inconsistently to warming, suggesting that responses to surface soil moisture stress induced by warming differ in sensitivity between functional groups. Deep-rooted, late-flowering plants exhibited phenological processes less constrained by soil moisture compared to shallow-rooted

early- and mid-flowering plants (Zhu, 2016). Dorji et al. (2013) found that warming delayed reproductive phenology of shallow-rooted early-flowering *Kobresia pygmaea* due to limited upper soil water availability. Other studies indicate that warming advanced budding and flowering phenology of dominant species *Saussurea nigrescens* and *Gentianopsis paludosa* by 5–8 days, while causing no significant phenological changes in *Ranunculus tanguticus* (Ashe, 2013).

Comparative phenological studies of alpine meadows and swamp meadows in permafrost regions demonstrate that at the community level, both low- and high-magnitude warming significantly advanced green-up dates in both meadow types. At the species level, low-magnitude warming significantly advanced green-up dates for five of seven species in alpine meadows and three of four species in alpine swamp meadows, while high-magnitude warming advanced green-up dates for all species in both meadow types. Except for low-magnitude warming in swamp meadows, warming significantly delayed plant withering times in both meadow types, with alpine meadows showing higher temperature sensitivity across all phenological stages than swamp meadows (Zhang, 2016).

Warming advances green-up dates and delays withering dates for communities and most species, thereby extending the growing season (Zhou et al., 2000; Zhang, 2016). Most studies attribute phenological changes primarily to temperature and precipitation variations (Wang et al., 2014a), though some identify soil thaw timing and moisture content as the main factors (Shen, 2011; Dorji et al., 2013). Soil moisture affects early-flowering plants more than mid- or late-flowering species, with early-flowering plants being more susceptible to soil water limitations following OTC warming during early growing seasons (Wang et al., 2016; Zhu, 2016). Since alpine meadows are closely associated with permafrost, warming advances permafrost thaw timing and thickens the active layer, altering hydrological conditions and causing asymmetric responses among different functional groups that modify original community phenological patterns (Wang et al., 2016).

## 1.2 Effects of Warming on Community Structure

Low temperature represents a key limiting factor for plant growth in Tibetan Plateau alpine grasslands, and simulated warming partially satisfies plant heat requirements, facilitating growth and development. While affecting plant phenology, warming also alters interspecific relationships, influencing plant community structure and composition. Liu et al. (2010) reported that total community coverage in alpine meadows showed an increasing trend over years, with average plant height positively correlated with temperature and experimental duration. However, other studies found no significant changes in community coverage under warming (Zhao, 2016; Shi et al., 2008). Zong et al. (2016) demonstrated that both year-round and winter warming significantly reduced community coverage in northern Tibetan alpine meadows, attributing this reduction primarily to decreased soil water content caused by warming during low-rainfall seasons. Warming experiments across different altitudinal gradients

revealed that warming significantly reduced community coverage at 4313 m but showed non-significant negative effects at 4513 m and 4693 m (Fu et al., 2013). Ganjurjav et al. (2016) found that warming significantly increased community height in both alpine meadows and alpine steppes, with no significant effect on alpine meadow coverage but a significant reduction in alpine steppe coverage. Conversely, other studies suggest that warming alleviates low-temperature constraints on plant growth, leading to increased alpine steppe community coverage (Chen et al., 2014).

Even within the same region, different vegetation types exhibit inconsistent community structure responses to simulated warming (Zhao et al., 2015; Li et al., 2011). Li et al. (2011) reported that warming increased community height in both alpine meadows and swamp meadows in permafrost regions of Fenghuoshan, with no significant effect on alpine meadow coverage but significantly increased swamp meadow coverage. Zhao et al. (2015) found that simulated warming significantly increased average height in both alpine meadows and alpine shrub meadows in the Haibei region, increased shrub meadow coverage, but caused no significant changes in alpine meadow coverage.

Different species and functional types exhibit varying temperature adaptability and sensitivity, resulting in distinct adaptive patterns under warming. Alpine meadow studies show that warming increased gramineous plant coverage while decreasing forb coverage (Shi et al., 2008), enhanced gramineous and forb functional group coverage while reducing sedge coverage, and promoted gramineous and forb growth while inhibiting sedge growth (Pang et al., 2016). However, other studies found no significant warming effects on gramineous or forb coverage (Ganjurjav et al., 2016). Li et al. (2011) observed that warming reduced gramineous and sedge coverage while increasing forb coverage in alpine meadows. Zong et al. (2016) concluded that warming inhibited growth of most plant functional groups in semi-arid alpine meadows, reducing coverage of gramineous plants, sedges, Asteraceae, and other forbs.

Alpine steppe studies indicate that warming significantly increased coverage of gramineous, sedge, and forb families without significantly affecting legume coverage (Chen et al., 2014). Conversely, other research found that warming significantly increased legume coverage while decreasing gramineous and forb coverage in alpine steppes, attributing these changes to soil moisture variations (Ganjurjav et al., 2016). Studies of alpine swamp meadows show that warming increased gramineous and sedge coverage while decreasing forb coverage (Li et al., 2011).

### 1.3 Effects of Warming on Species Diversity

Differential responses among species and functional groups to climate warming alter existing community interspecific relationships, modifying community structure and species diversity, which subsequently influences community succession rates and directions. In alpine meadows, experimental warming reduced species

richness by 26-36%, with greater diversity loss in areas with low soil nutrients and water content. Due to differing temperature sensitivities between medicinal and edible forage species, medicinal plant species declined by 21% while non-medicinal plants decreased by 40% (Klein et al., 2004). However, Wang et al. (2012), using infrared warming in the same region, found only approximately 10% species richness reduction. These differing magnitudes of species richness decline may relate to different experimental warming apparatuses. Li et al. (2004) reported that five years of simulated warming in *Kobresia humilis* meadows significantly reduced species richness, increased drought-tolerant gramineous proportions, and decreased forb proportions. Nevertheless, other experiments showed no significant warming effects on alpine meadow community richness or Shannon-Wiener diversity index (Li et al., 2011; Zhao et al., 2015), with community species composition remaining unchanged and only species dominance shifting (Shi et al., 2008).

In alpine steppes, short-term simulated warming did not affect community species richness but altered species importance values, increasing proportions of drought-tolerant gramineous species such as *Calamagrostis pseudophragmites* while decreasing toxic weed proportions represented by *Oxytropis falcata* (Chen et al., 2014). However, other studies indicate that warming significantly reduced alpine steppe community richness (Ganjurjav et al., 2016).

In alpine swamp meadows, warming showed no significant effect on species richness (Li et al., 2011), though other research demonstrated that loss of sedge species caused significant reductions in species richness and Shannon-Wiener index (Yang et al., 2015). In alpine shrub meadows, warming significantly increased dominant species height and coverage, altering energy balance and competition patterns for light and space, suppressing other species and consequently reducing species richness and Shannon-Wiener index (Zhao et al., 2015).

#### 1.4.1 Effects of Warming on Aboveground Biomass

Simulated warming alters microclimate conditions within plant communities, affecting photosynthesis and growth rates, thereby influencing plant development and biomass. Warming experiments across different Tibetan Plateau regions have produced varying or even contradictory results, consistent with meta-analysis conclusions for tundra plant communities showing regional differences in biomass responses to warming (Elmendorf et al., 2012). For example, some alpine meadow studies indicate that warming significantly increased aboveground biomass (Ganjurjav et al., 2016; Liu et al., 2010; Guo et al., 2015; Li et al., 2011a), while others show no significant changes (Fu et al., 2013; Wang, 2016; Shi et al., 2008; Zhou et al., 2000). Some studies demonstrate that warming reduced aboveground alpine meadow biomass, attributing this reduction to soil moisture stress caused by warming-induced thermal effects (Klein et al., 2004; Li et al., 2004). Fu et al. (2013) found that experimental warming significantly reduced biomass at 4313 m altitude but had no significant effects at 4513 m and 4693 m.

Even within the same region, different grassland types show inconsistent responses to simulated warming. Yu et al. (2015) reported that warming decreased aboveground biomass in *Kobresia humilis* meadows while increasing it in *Dasiphora fruticosa* shrub meadows, though neither effect was significant. Li et al. (2011) found that warming promoted biomass increases in both alpine meadows and swamp meadows in permafrost regions, but high-magnitude warming suppressed this promotion in alpine meadows while enhancing it in swamp meadows. This suggests that because natural conditions and soil hydrothermal regimes differ between alpine meadows and swamp meadows, drought conditions induced by high-magnitude warming may weaken the biomass increase caused by temperature elevation in alpine meadows.

Alpine steppe studies show that warming significantly reduced aboveground biomass, suggesting that if temperatures exceed ecosystem thresholds, warming effects on biomass depend on water availability (Ganjurjav et al., 2016).

Different species and functional groups exhibit varying adaptive capacities to environmental changes related to morphology and resource utilization, resulting in distinct growth and biomass allocation patterns under warming. Different functional groups may respond in opposite directions to climate warming (Klein et al., 2007; Li et al., 2011a), potentially explaining non-significant warming effects on community aboveground productivity in some studies (Klein et al., 2007). Compared to species richness, responses of dominant species or functional groups to temperature elevation determine community aboveground biomass responses. Warming significantly increased gramineous biomass (Shi et al., 2008), with non-significant effects on sedge biomass but significant reductions in forb biomass (Zhou et al., 2000; Shi et al., 2008). This may occur because warming accelerates growth rates of gramineous and sedge plants, suppressing forb growth and reducing forb biomass (Zhou et al., 2000). However, other studies found that warming increased forb biomass (Guo et al., 2015). In alpine steppes, warming altered gramineous tillering capacity and resource allocation patterns, enabling greater nutrient acquisition and significantly increasing gramineous biomass (Chen et al., 2014).

Responses of Tibetan Plateau grassland ecosystems to warming are influenced not only by region and vegetation type but also by experimental duration. Li et al. (2004) reported that in a five-year warming study of *Kobresia humilis* meadows, biomass was higher than control plots during initial warming years but declined after five years of warming.

Response patterns of different grassland ecosystems to warming show varying sensitivity weightings to temperature and moisture across regions (Wang et al., 2013). Alpine steppe aboveground biomass responses to climate warming are significantly smaller than those of alpine meadows, while responses to precipitation increases are greater than in alpine meadows (Wang et al., 2007). Tibetan Plateau alpine meadow aboveground biomass is closely related to climate conditions and significantly affected by permafrost environments, with vegetation coverage and biomass production showing significant decreasing trends

with increasing permafrost upper boundary depth (Wang et al., 2006). Climate warming promotes permafrost thaw and nutrient cycling, potentially increasing alpine plant productivity (Klady et al., 2011). However, plant communities exhibit lagged responses to long-term resource feedback, growth, and competition effects, and long-term warming may become constrained by environmental conditions such as water or nutrients, causing long-term responses to differ from short-term reactions (Elmendorf et al., 2012).

#### 1.4.2 Effects of Warming on Belowground Biomass

Temperature elevation affects plant communities not only aboveground but also belowground (He et al., 2004). Seasonal thaw depth of permafrost directly determines soil water and nutrient conditions in the vegetation root zone. Deep permafrost thawing due to temperature increases alters hydrological processes, and plants adjust belowground biomass investment to maximize growth requirements. Consistent with aboveground biomass, warming effects on belowground biomass have not reached unanimous conclusions. Alpine meadow studies show that warming significantly increased belowground biomass (Chen et al., 2016; Li et al., 2011), had no significant effect (Shi et al., 2012; Wang, 2016), or reduced belowground biomass under long-term warming (Yu et al., 2015). Studies of other alpine grassland ecosystems show that warming reduced belowground biomass in alpine shrub meadows (Yu et al., 2015) and increased belowground biomass in alpine swamp meadows by promoting growth and reproduction of fibrous-rooted gramineous and sedge plants (Li et al., 2011).

Warming not only altered root biomass but also changed its distribution across soil depths. Yu et al. (2015) found that long-term warming significantly reduced belowground biomass in the 0–10 cm layer for both alpine meadows and shrub meadows, shifting allocation patterns distinctly to deeper layers. Li et al. (2011) reported similar conclusions for permafrost region alpine meadows and swamp meadows: warming shifted alpine meadow biomass allocation patterns to deeper layers (though not significantly), while swamp meadow biomass clearly transferred to deeper soil layers.

While belowground biomass responses to experimental warming remain inconsistent, the shift in root biomass allocation to deeper layers may occur because plant root growth is closely related to soil moisture (Xu et al., 2016). OTC warming may enhance soil water evaporation, reducing surface soil water content and causing plant roots to grow deeper to obtain adequate nutrients and water (Yu et al., 2015). Alternatively, different functional groups exhibit substantial differences in root quantity and distribution, with deep-rooted species showing lower sensitivity to experimental warming while shallow-rooted species are more sensitive. Growth of plants with roots at different depths is affected by temperature and moisture, manifesting as changes in root biomass and allocation patterns across soil layers (Klein et al., 2008).

Temperature affects nutrient availability through biogeochemical feedbacks,

while precipitation influences vegetation growth by affecting soil water availability (Yang & Piao, 2006). Warming's primary effect on grassland ecosystems is altering ecosystem water balance, causing soil drought that subsequently affects grassland productivity. Ecosystem moisture conditions largely determine whether warming effects on productivity are positive, negative, or neutral (Mowll et al., 2015).

## 2.1 Effects of Warming on Soil Carbon and Nitrogen Content

Soil constitutes a critical component of grassland ecosystems, controlling nutrient cycling and availability while serving as the most active source and sink for organic carbon and nutrients, making it highly sensitive to global climate change (Li et al., 2011b). Alpine meadow studies show that warming significantly increased soil ammonium and nitrate nitrogen content without affecting total soil nitrogen (Shi et al., 2012), significantly increased total soil organic carbon and total nitrogen without affecting available nitrogen, nitrate, or ammonium (Ganjurjav et al., 2016), and had similar effects under short- and long-term warming: significantly increasing ammonium nitrogen while showing no significant effects on total carbon, total nitrogen, organic carbon, or nitrate nitrogen (Wang et al., 2014b). Changes in soil organic carbon, dissolved organic carbon, total nitrogen, dissolved nitrogen, dissolved organic nitrogen, ammonium, and nitrate require long-term processes, with short-term warming showing no significant effects (Wang, 2016).

Warming effects on alpine meadow soil carbon and nitrogen content depend not only on the specific metrics but also on soil depth. For example, warming reduced surface soil (0-5 cm) organic carbon and 0-20 cm total nitrogen (Heng et al., 2011a). Low- and high-magnitude warming increased 0-5 cm soil organic carbon and total nitrogen while decreasing them in the 5-20 cm layer (Li et al., 2010). Other studies found no significant changes in 0-20 cm soil carbon but increased organic carbon in the 20-30 cm layer (Yu et al., 2015).

Studies of other alpine grassland ecosystems show that warming significantly increased available nitrogen while reducing total organic carbon and total nitrogen in alpine steppes, with no significant effects on nitrate or ammonium (Ganjurjav et al., 2016). Warming accelerated surface soil organic carbon decomposition and root litter addition, reducing organic carbon and total nitrogen in the 0-5 cm surface layer of swamp meadows while increasing them in the 5-20 cm layer (Li et al., 2010). In alpine shrub meadows, warming showed no significant effect on 0-20 cm soil carbon but reduced soil carbon in the 20-30 cm layer (Yu et al., 2015).

## 2.2 Effects of Warming on Soil Microbial Carbon and Nitrogen

Soil microorganisms constitute essential soil components and primary participants in soil material cycling and energy flow. Temperature is a crucial factor affecting soil microbial activity, and microbial responses to warming represent

important components of ecosystem feedback processes. Alpine meadow studies indicate that temperature elevation causes exponential increases in microbial respiration, accelerating organic carbon mineralization, enhancing microbial activity, and increasing microbial biomass carbon and nitrogen (Wang et al., 2011; Shi et al., 2012; Li et al., 2011b), with moderate warming affecting surface soil microbial biomass more than deep soil (Li et al., 2011b). However, other studies show minimal warming effects on soil microbial biomass carbon and nitrogen content and ratios, suggesting that combined effects of other environmental factors may offset warming effects (Fu et al., 2012; Heng et al., 2011b), and that long- and short-term warming have no significant effects on soil microbial carbon and nitrogen (Wang et al., 2014b).

Alpine swamp meadow studies show that 2.98°C warming increased soil microbial biomass carbon and nitrogen, with greater surface than deep soil effects, while 5.52°C warming decreased microbial biomass carbon and nitrogen, with deeper soils more affected than surface layers (Li et al., 2011b).

Generally, temperature elevation increases soil microbial physiological activity and accelerates soil carbon and nitrogen cycling (Zhou et al., 2010). However, high temperatures and reduced soil moisture may disrupt fundamental microbial characteristics, inhibiting microbial activity (Contin et al., 2000). A meta-analysis revealed that under warming conditions, soil microbial carbon and nitrogen are influenced by mean annual precipitation, with smaller negative effects of soil moisture decline on microbial growth in regions with higher precipitation, resulting in more pronounced microbial biomass increases due to temperature elevation (Wang et al., 2015). Warming may increase soil carbon and nitrogen content and microbial biomass, while changes in other environmental factors such as moisture and their interactions may cause decreases. Combined effects of various factors may accelerate or offset soil carbon and nitrogen cycling rates, creating uncertainty.

## Discussion and Future Research Directions

The vast Tibetan Plateau features complex topography with substantial regional differences in temperature and precipitation, resulting in tremendous variation in grassland community structure and function (Wang et al., 2013). Consequently, communities in different regions and types exhibit differential responses to climate change. Under global change, spatial patterns of Tibetan Plateau grassland ecosystems have undergone important changes, with alpine steppe distribution areas increasing while alpine meadows and swamp meadows have significantly contracted (Chen et al., 2015). Vegetation phenology and productivity show clear spatiotemporal differences, with remote sensing monitoring indicating advanced phenology in northeastern Tibetan Plateau regions, delayed phenology in southwestern regions, increased grassland productivity in eastern areas, and decreased productivity in western areas (Chen et al., 2015).

Current mechanisms underlying climate change effects on Tibetan Plateau

alpine grassland productivity remain unclear, with different alpine grassland ecosystems showing varying response patterns influenced by region, community type, and experimental duration. Under warming conditions, soil moisture changes induced by precipitation and permafrost active layer dynamics regulate ecosystem responses to climate warming by controlling phenology, community structure, productivity, and soil processes. Only through correct understanding of response patterns and mechanisms can we better address climate change, curb grassland degradation, and maintain ecosystem stability. Based on current research, we recommend prioritizing the following areas:

1. **Scaling limitations:** OTC experiments face spatial and temporal scaling limitations that create difficulties in extrapolating results or providing parameters for models. Different warming methods vary in design, technology, and warming mechanisms, complicating meta-analyses and increasing model prediction uncertainty. Future research should establish multiple warming apparatuses at the same site within the same ecosystem type to integrate and analyze grassland ecosystem responses to different warming methods, improving model parameter estimation and validation.
2. **Interspecific competition:** Natural species/functional groups occupy unique ecological niches, yet existing research focuses on entire community ecosystems while ignoring interspecific competition mechanisms. Ecosystem succession and development under climate change result from competitive interactions among species/functional groups. Future studies should examine community species evolution over time, niche differentiation, and competitive relationships under global warming.
3. **Permafrost coupling:** Tibetan Plateau permafrost environments significantly influence vegetation community structure, diversity, and biomass, but existing research has not considered regional permafrost differences or permafrost thaw effects on grassland ecosystems. Future research should couple abiotic factors including permafrost, temperature, and moisture to clarify influence weightings of various factors in different grassland ecosystem types under global warming.

## References

- Ashe XH, 2013. Effects of warming and precipitation regime on plant phenology and productivity in an alpine meadow, northwestern Sichuan, China [D]. Chengdu: Chengdu University of Technology.
- Chen DL, Bai QX, Yao TD, et al, 2015. Assessment of past, present and future environmental changes on the Tibetan Plateau [J]. Chinese Science Bulletin, 60(32): 3025-3035.
- Chen J, Cao JJ, Jin Z, et al, 2014. The influence of short-term experimental warming on alpine steppe of Bird Island, Qinghai Lake [J]. Journal of Arid Land Resources and Environment, 28(5): 127-133.

- Chen J, Luo Y, Xia J, et al, 2016. Differential responses of ecosystem respiration components to experimental warming in a meadow grassland on the Tibetan Plateau [J]. *Agricultural and Forest Meteorology*, 220: 21-29.
- Contin M, Corcimarú S, De Nobili M, et al, 2000. Temperature changes and the ATP concentration of the soil microbial biomass [J]. *Soil Biology and Biochemistry*, 32(8): 1219-1225.
- Dorji T, Totland O, Moe SR, et al, 2013. Plant functional traits mediate reproductive phenology and success in response to experimental warming and snow addition in Tibet [J]. *Global Change Biology*, 19(2): 459-472.
- Elmendorf SC, Henry GHR, Hollister RD, et al, 2012. Plot-scale evidence of tundra vegetation change and links to recent summer warming [J]. *Nature Climate Change*, 2(6): 453-457.
- Fu G, Shen Z, Zhang X, et al, 2012. Response of soil microbial biomass to short-term experimental warming in alpine meadow on the Tibetan Plateau [J]. *Applied Soil Ecology*, 61: 158-160.
- Fu G, Zhang X, Zhang Y, et al, 2013. Experimental warming does not enhance gross primary production and above-ground biomass in the alpine meadow of Tibet [J]. *Journal of Applied Remote Sensing*, 7: 6451-6465.
- Ganjurjav H, Gao Q, Gornish ES, et al, 2016. Differential response of alpine steppe and alpine meadow to climate warming in the central Qinghai-Tibetan Plateau [J]. *Agricultural and Forest Meteorology*, 223: 233-240.
- Guo HY, De KJ, Lu GX, et al, 2015. The impacts of simulative warming and adding nitrogen on the grassland productivity of alpine meadow [J]. *Acta Agrestia Sinica*, 23(2): 322-327.
- He JS, Wang ZQ, Fang JY, 2004. Issues and prospects of belowground ecology with special reference to global climate change [J]. *Chinese Science Bulletin*, 49(13): 1226-1233.
- Heng T, Wu J, Xie SY, et al, 2011a. The responses of soil C and N, microbial biomass C or N under alpine meadow of Qinghai-Tibet Plateau to the change of temperature and precipitation [J]. *Chinese Agricultural Science Bulletin*, 27: 425-430.
- Imhoff ML, Bounoua L, Ricketts T, et al, 2004. Global patterns in human consumption of net primary production [J]. *Nature*, 429(6994): 870-873.
- IPCC. 2013. *Climate Change: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
- Klady RA, Henry GHR, Lemay V, 2011. Changes in high arctic tundra plant reproduction in response to long-term experimental warming [J]. *Global Change Biology*, 17(4): 1611-1624.

- Klein JA, Harte J, Zhao XQ, 2007. Experimental warming, not grazing, decreases rangeland quality on the Tibetan Plateau [J]. *Ecological Applications*, 17(2): 541-557.
- Klein JA, Harte J, Zhao XQ, 2004. Experimental warming causes large and rapid species loss, dampened by simulated grazing, on the Tibetan Plateau [J]. *Ecology Letters*, 7(12): 1170-1179.
- Klein JA, Harte J, Zhao XQ, 2008. Decline in medicinal and forage species with warming is mediated by plant traits on the Tibetan Plateau [J]. *Ecosystems*, 11(5): 775-789.
- Li N, Wang GX, Gao YH, et al, 2010. Effects of simulated warming on soil nutrients and biological characteristics of alpine meadow soil in the headwaters region of the Yangtze River [J]. *Acta Pedologica Sinica*, 47(6): 1214-1224.
- Li N, Wang GX, Gao YH, et al, 2011b. Warming effects on plant growth, soil nutrients, microbial biomass and soil enzymes activities of two alpine meadows in Tibetan Plateau [J]. *Polish Journal of Ecology*, 59(1): 25-35.
- Li N, Wang GX, Yang Y, et al, 2011a. Plant production, and carbon and nitrogen source pools, are strongly intensified by experimental warming in alpine ecosystems in the Qinghai-Tibet Plateau [J]. *Soil Biology and Biochemistry*, 43(5): 942-953.
- Li N, Wang GX, Yang Y, et al, 2011. Short-term effects of temperature enhancement on community structure and biomass of alpine meadow in the Qinghai-Tibet Plateau [J]. *Acta Ecologica Sinica*, 31(4): 895-905.
- Li Y, Zhao L, Zhao XQ, et al, 2004. Effects of a 5-years mimic temperature increase to the structure and productivity of *Kobresia humilis* meadow [J]. *Acta Agrestia Sinica*, 12(3): 236-239.
- Liu W, Wang CT, Zhao JZ, et al, 2010. Responses of quantity characteristics of plant community to simulating warming in alpine *Kobresia humilis* meadow ecosystem [J]. *Acta Botanica Boreali-Occidentalia Sinica*, 30(5): 995-1003.
- Liu X, Chen B, 2000. Climatic warming in the Tibetan Plateau during recent decades [J]. *International Journal of Climatology*, 20(14): 1729-1742.
- Mowl W, Blumenthal DM, Cherwin K, et al, 2015. Climatic controls of above-ground net primary production in semi-arid grasslands along a latitudinal gradient portend low sensitivity to warming [J]. *Oecologia*, 177(4): 959-969.
- Niu SL, Han XG, Ma KP, et al, 2007. Field facilities in global warming and terrestrial ecosystem research [J]. *Journal of Plant Ecology*, 31(2): 262-271.
- Pang XY, Lei JP, Wang A, et al, 2016. Response of plant community in sub-alpine meadow to climate change [J]. *Acta Botanica Boreali-Occidentalia Sinica*, 36(8): 1678-1686.

- Pau S, Wolkovich EM, Cook BI, et al, 2011. Predicting phenology by integrating ecology, evolution and climate science [J]. *Global Change Biology*, 17(12): 3633-3643.
- Piao SL, Cui M, Chen A, et al, 2011. Altitude and temperature dependence of change in the spring vegetation green-up date from 1982 to 2006 in the Qinghai-Xizang Plateau [J]. *Agricultural and Forest Meteorology*, 151(12): 1596-1604.
- Richardson AD, Keenan TF, Migliavacca M, et al, 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system [J]. *Agricultural and Forest Meteorology*, 169: 156-173.
- Richardson SJ, Hartley SE, Press MC, 2000. Climate warming experiments: are tents a potential barrier to interpretation? [J]. *Ecological Entomology*, 25(3): 367-370.
- Shen M, 2011. Spring phenology was not consistently related to winter warming on the Tibetan Plateau [J]. *Proceedings of the National Academy of Sciences*, 108(19): E91.
- Shi F, Chen H, Chen H, et al, 2012. The combined effects of warming and drying suppress CO<sub>2</sub> and N<sub>2</sub>O emission rates in an alpine meadow of the eastern Tibetan Plateau [J]. *Ecological Research*, 27(4): 725-733.
- Shi FS, Wu N, Luo P, 2008. Effect of temperature enhancement on community structure and biomass of subalpine meadow in Northwestern Sichuan [J]. *Acta Ecologica Sinica*, 28(11): 5286-5293.
- Thomas CD, Cameron A, Green RE, et al, 2004. Extinction risk from climate change [J]. *Nature*, 427(6970): 145-148.
- Walther G-R, Post E, Convey P, et al, 2002. Ecological responses to recent climate change [J]. *Nature*, 416(6879): 389-395.
- Wang B, Sun G, Luo P, et al, 2011. Labile and recalcitrant carbon and nitrogen pools of an alpine meadow soil from the eastern Qinghai-Tibetan Plateau subjected to experimental warming and grazing [J]. *Acta Ecologica Sinica*, 31(6): 1506-1514.
- Wang CS, Meng FD, Li XE, et al, 2013. Responses of alpine grassland ecosystem on Tibetan Plateau to climate change: A mini review [J]. *Chinese Journal of Ecology*, 32(6): 1587-1595.
- Wang GX, Hu HC, Wang YB, et al, 2007. Response of alpine cold ecosystem biomass to climate changes in permafrost regions of the Tibetan Plateau [J]. *Journal of Glaciology and Geocryology*, 29(5): 671-679.
- Wang GX, Li YS, Wu QB, et al, 2006. Relationship between frozen soil and vegetation in permafrost regions of Tibetan Plateau and the effect on the alpine ecosystem [J]. *Science in China Series D: Earth Sciences*, 36(8): 743-754.

- Wang R, 2016. Effects of warming and precipitation enhancement on soil and plant carbon and nitrogen of alpine meadow ecosystem [D]. Lanzhou: Gansu Agricultural University.
- Wang SP, Duan JC, Xu G, et al, 2012. Effects of warming and grazing on soil N availability, species composition, and ANPP in an alpine meadow [J]. *Ecology*, 93(11): 2365-2376.
- Wang SP, Meng FD, Duan JC, et al, 2016. Asymmetric sensitivity of first flowering date to warming and cooling in alpine plants [J]. *Ecology*, 95(12): 3387-3398.
- Wang SP, Wang C, Duan JC, et al, 2014a. Timing and duration of phenological sequences of alpine plants along an elevation gradient on the Tibetan plateau [J]. *Agricultural and Forest Meteorology*, 189-190: 220-228.
- Wang WL, Kong WD, Zeng H, et al, 2015. A meta-analysis of responses of soil microbes to warming [J]. *Journal of Agro-Environment Science*, 34(11): 2169-2175.
- Wang X, Dong S, Gao Q, et al, 2014b. Effects of short-term and long-term warming on soil nutrients, microbial biomass and enzyme activities in an alpine meadow on the Qinghai-Tibet Plateau of China [J]. *Soil Biology and Biochemistry*, 76: 140-142.
- Xu MH, Liu M, Zhai DT, et al, 2016. Dynamic changes in biomass and its relationship with environmental factors in an alpine meadow on the Qinghai-Tibetan Plateau, based on simulated warming experiments [J]. *Acta Ecologica Sinica*, 36(18): 5759-5767.
- Xu MH, Xue X, 2013. A research on summer vegetation characteristics & short-time responses to experimental warming of alpine meadow in the Qinghai-Tibetan Plateau [J]. *Acta Ecologica Sinica*, 33(7): 2071-2083.
- Yang Y, Wang GX, Klanderud K, et al, 2015. Plant community responses to five years of simulated climate warming in an alpine fen of the Qinghai-Tibetan Plateau [J]. *Plant Ecology & Diversity*, 8(2): 211-218.
- Yang YH, Piao SL, 2006. Variations in grassland vegetation cover in relation to climatic factors on the Tibetan plateau [J]. *Journal of Plant Ecology*, 30(1): 1-8.
- Yu XC, Yao BQ, Zhou HK, et al, 2015. Variable responses of long-term simulated warming of underground biomass and carbon allocations of two alpine meadows on the Qinghai-Tibet Plateau [J]. *Chinese Science Bulletin*, 60(4): 379.
- Zhang L, Wang GX, Ran F, et al, 2018. Experimental warming changed plants' phenological sequences of two dominant species in an alpine meadow, western Sichuan [J]. *Chinese Journal of Plant Ecology*, 42(1): 20-27.
- Zhang T, 2016. The effect of experimental warming on the carbon cycle of alpine meadow ecosystems in the permafrost region of Qinghai-Tibet Plateau

[D]. Beijing: University of Chinese Academy of Sciences.

Zhao YY, 2016. The physiological and ecological response of typical alpine meadow plants to warming and simulated grazing [D]. Beijing: University of Chinese Academy of Sciences.

Zhao YY, Zhou HK, Yao BQ, et al, 2015. The influence of long-term simulating warming to the plant community and soil nutrient of alpine meadow [J]. *Acta Agrestia Sinica*, 23(4): 665-671.

Zhou HK, Zhou XM, Zhao XQ, 2000. A preliminary study of the influence of simulated greenhouse effect on a *Kobresia humilis* meadow [J]. *Acta Phytoecologica Sinica*, 24(5): 547-553.

Zhou X, Wan S, Luo Y, 2010. Source components and interannual variability of soil CO<sub>2</sub> efflux under experimental warming and clipping in a grassland ecosystem [J]. *Global Change Biology*, 13(4): 761-775.

Zhu JT, 2016. Effects of experimental warming on plant reproductive phenology in Xizang alpine meadow [J]. *Chinese Journal of Plant Ecology*, 40(10): 1028-1036.

Zong N, Xi C, Shi PL, et al, 2016. Responses of plant community structure and species composition to warming and N addition in an alpine meadow, northern Tibetan Plateau, China [J]. *Chinese Journal of Applied Ecology*, 27(12): 3739-3748.

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