A Review of the Global Change Research on the Tibetan Plateau: From Field Observation to Manipulative Experiments

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Abstract: Global temperature increases and precipitation changes are both expected to alter alpine ecosystem structure and processes. In this paper, we reviewed the recent climate changes observed and the global change researches on the Tibetan Plateau. Firstly, we found that the mean annual temperature and precipitation (data from 75 meteorological stations, where all daily precipitation data are available) have increased since 1971, there were 0.5˚C and 0.7˚C per decade increase in annual and winter temperature, respectively, on Tibetan Plateau, and changes in precipitation were found both less spatially and temporally consistent. Secondly, we reviewed the climate change researches on the Tibetan Plateau published between 2000 and 2019 mainly focused on plant growth and ecosystem carbon balance which including plant phenology, plant productivity, plant diversity, exchanges in ecosystem carbon and soil organic carbon. Findings and insights from these studies have been very useful to understand how the alpine ecosystem processes respond to climate change. However, the effects of temperature increase on plant growth and ecosystem carbon balance are differ depending on the study sites and warming methods and periods, and the effects of precipitation changes are sparse.

Keywords: Climate change, Plant phenology, Plant productivity and diversity, Soil organic carbon, Ecosystem carbon dynamics, Tibetan Plateau.

1. INTRODUCTION

The Tibetan Plateau, covering an area of 2.5 million km^2 with an average elevation of over 4000 m above sea level, is regarded as the third pole of the world and the highest unique territorial unit in the world [1-2]. The Plateau is characterized by monsoon climate with long, cool and dry winter and a relatively short, wet and humid summer [3]. Low temperatures and short growing seasons are considered to be important limiting factors controlling the ecosystem processes. According to the previous estimates, SOC (soil organic carbon) stock (4.4 Pg C) in alpine grasslands on the Tibetan Plateau accounts for 13.3% of China’s total SOC stock (32.9 Pg C) in the top 30cm depth [4]. Due to its unique climate and vegetation types and the large stocks of SOC, the Tibetan Plateau is considered to be particularly sensitive to global climate change [5] and has attracted a number of scientists to explore the feedback between ecosystem processes and climate change, which can substantially affect the global carbon budget [6].

Since 1950s, some studies have studied climate change on the Tibetan Plateau based on observational data from meteorological stations and remote sensing [3,7-9]. Tibetan Plateau is experiencing significantly climate warming and spatially heterogeneous precipitation changes as summarized in by Kang *et al*. [3]. The climate on the Qinghai-Tibet Plateau continues to warm [10]. Many studies attempt to explore the feedback between climate change and ecosystem structure and processes using field observations, manipulative experiments, models and large-scale remote sensing on the Tibetan Plateau [6,11]. The models used for future or large-scale assessments are built upon knowledge from field observation and manipulative experiments [12]. Until now, hundreds of global changes manipulate experiments have been conducted on the Tibetan Plateau [6,13]. Most of these studies found that climate warming has significantly changed alpine ecosystem structure and processes on the Tibetan Plateau. These changes include alteration in plant community phenology, structure, composition, litter decomposition rate, greenhouse gases emission and SOC stocks [14-22]. However, there are few studies on changes in precipitation or the interaction of warming and precipitation changes on ecosystem structure and processes on the Tibetan Plateau. Since the global change research conducted is non-systematic and limited, it is difficult to find a consistent trend of alpine ecosystem structure and processes against the on-going climate change on the Tibetan

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Plateau. In view of this, it is critical to synthesize the major findings from manipulative experiments that have examined the responses of alpine ecosystem structure and processes to climate change for future research projects.

In this synthesis, we reviewed the climate changes and recent global change research findings of the past and ongoing global change research on the Tibetan Plateau and introduced our new climate research platform. The aim of this review was to (1) analyse the recent climate change characteristics of the Tibetan Plateau; (2) provide a comprehensive analysis of the past and ongoing global change researches on the Tibetan Plateau; (3) suggest future directions for global change researches on the Tibetan Plateau on the basis of synthesis.

2.OBSERVED CHANGES IN CLIMATE ON THE TIBETAN PLATEAU

2.1. Temperature

Global mean temperature is predicted to increase by 1.8~4.0^{o}C till the end of this century. The Tibetan Plateau has been reported to be an extremely sensitive region to global climate change and this region is predicted to experience “much greater than average” increases in temperatures (1.3~6.9^{o}C) in the future [23].

Since 1950s, a number of meteorological stations have been established on the Tibetan Plateau. However, previous studies showed inconsistent results due to the different time period or meteorological stations examined. During 1955-1996, the linear trends of mean annual temperature (MAT) and winter temperature (December-February) averaged over 97 meteorological stations on the Tibetan Plateau reached 0.016^{o}C yr^{-1} and 0.032^{o}C yr^{-1}, respectively [7]. The MAT dataset from 90 meteorological stations on the Tibetan Plateau during 1960-2007 showed that MAT has increased by 0.036^{o}C yr^{-1} [24]. Based on the MAT dataset during 1960-2006, Piao *et al*. [25] reported that the MAT has increased by ~0.03^{o}C yr^{-1} on the Tibetan Plateau since 1960. Summer warming and autumn warming have the same rate with mean annual warming. Winter warming (~0.05^{o}C yr^{-1}) has the higher rate than mean annual warming, but spring warming (~0.02^{o}C yr^{-1}) has the lowest rate.

We reanalyzed MAT from 1971 to 2010 over 75 meteorological stations across the Tibetan Plateau, and found that the MAT has increased by ~0.05^{o}C yr^{-1} since 1971, with the largest increasing rate of 0.07^{o}C per year observed in winter (Fig. **1a** and **1c**). This is consistent with the results of regional modeling. Models indicated that temperatures are expected to increase to a significantly greater extent in the non-growing season than in the growing season, particularly at high altitudes [23].

2.2. Precipitation

In contrast to the trend of temperature, changes in precipitation are less evident spatially consistent and there is a larger inter-annual variability [3]. Furthermore, precipitation has occurred in a more concentrated way on regional scale, which has increased in most regions and has reduced in a few regions during the same period on the Tibetan Plateau [3,7]. There is a slight increase in annual total precipitation on the Tibetan Plateau over the past several decades, but precipitations in spring and winter have increased significantly during 1960-2006 [25]. We analyzed data from 75 meteorological stations and observed a significant increasing trend in averaged precipitation during 1971-2010 (Fig. **1b**). The Tibetan Plateau is experiencing more precipitation during both spring and summer (0.9~1.1mm per year). This is consistent with the view of Gautam *et al*. who explained the warming trend of the Himalayas from the perspective of aerosols, and pointed out that this trend can not only bring about changes in monsoon rainfall in the region, but also affect its hydrological cycle [26]. By contrast, there is less precipitation in autumn and winter on the Tibetan Plateau since 1971 (Fig.**1d**), which was inconsistent with the previous results indicated by Piao *et al*. [25].

3.MAJOR FINDINGS OF GLOBAL CHANGE RESEARCHES ON THE TIBETAN PLATEAU

During recent decades several studies from field observation have been conducted to quantify the response of ecosystem processes on climate change on the Tibetan Plateau (Fig. **2**, Table **1**). Most of these studies studied on the ecological process of carbon dynamics and the large-scale spatial pattern of C sequestration across the vast plateau (Table **2**) [6], including carbon storage and dynamics in permafrost regions of the Tibetan Plateau [27]. These studies mainly focused on:

3.1. Phenological Responses

Climate change has influenced the timing of stages of development of most plants in the temperate and cold regions [5,8,28,29]. For example, Yu *et al*. [29] reported that the onset of the growing season was

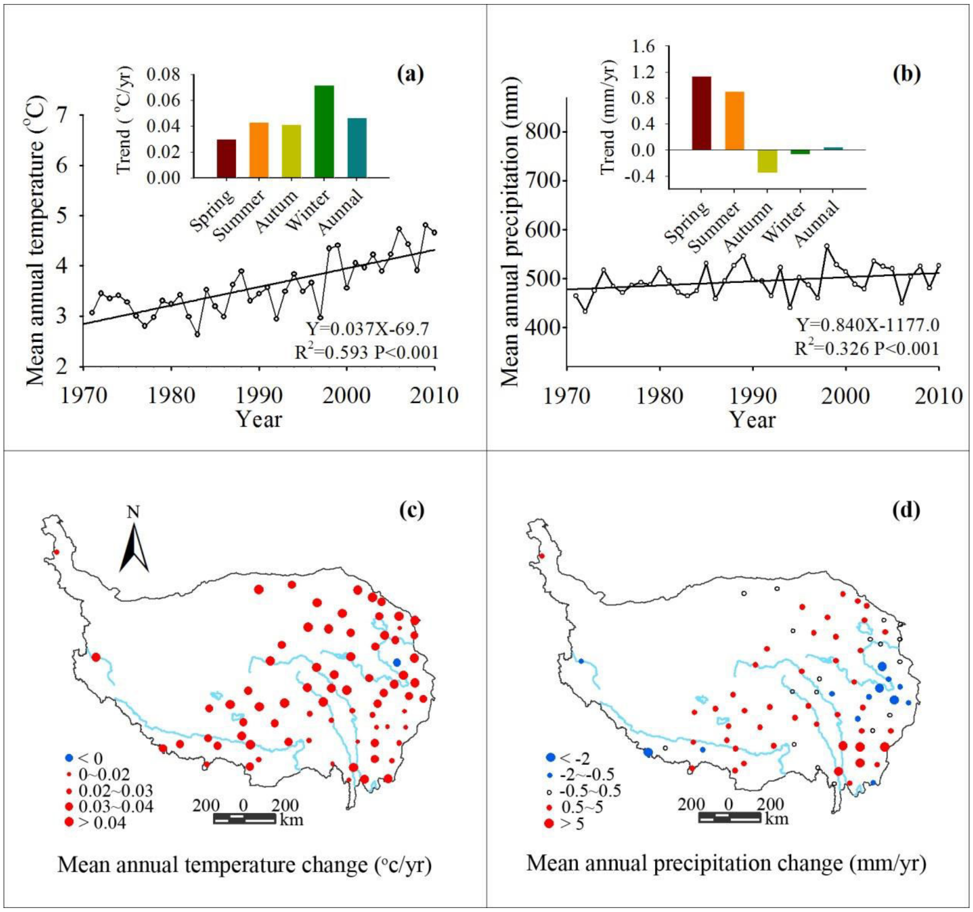

Figure :1 Observed trends of air temperature and precipitation from 1971 to 2010 on the Tibetan Plateau. The data are from the climate records of 75 meteorological stations, where all daily precipitation data are available. a, Mean annual temperature (MAT), with the inset showing trends in seasonal temperature (°C per year) during the period 1971–2010. The straight line is a fit to the data: Y=0.037X-69.7 (R^2= 0.593, p<0.001). b, Mean annual precipitation (MAP), with the inset showing trends in seasonal precipitation (mm per year) during the period 1971–2010. The straight line is a fit to the data: Y=0.840X-1177.0 (R^2= 0.326, p<0.001). c, Spatial patterns of the trend of MAT changes from 1971 to 2010. d, Spatial patterns of the trend of MAP changes from 1971 to 2010.

delayed since the mid-1990s based on the field observation, and probably due to the increase in winter temperatures, because winter warming could delay the fulfillment of the chilling requirement, which slows the dormancy breaking process. Differing from the assumption of Yu *et al*. [29], Shen [30] demonstrated that the effect of winter warming on the spring phenology does not follow a simple correlation and further analysis using a dataset of long-term is needed to address this effect. After analyzing the European phenology, Jochner *et al*. also found that changes in plant phenology cannot establish a perfect linear relationship with temperature [31]. Similarly, Chen *et al*. [32] suggested that the causes of the delay spring starting green time should include several factors such as thawing-freezing processes, climate changes, grassland degradation, and their combined effect rather than a single factor. Used satellite derived NDVI (Normalized Difference Vegetation Index) data, Piao *et al*. [8] found that the vegetation starting green time significantly advanced by 0.88 day year $^{-1}$ from 1982 to 1999, but significantly delayed from 1999 to 2006 and no significant trend from 1982 to 2006 was observed. But this is somewhat different from Ge *et al*.'s [33] view. Ge *et al*. conducted a META analysis of China's 1263 phenological time series from 1960 to 2011 and found that the spring and summer phenology has a clear trend in advance, but the autumn phenology changes are more complex.Gao *et al*. [35] also believes that autumn phenological changes are complicated.They used global satellite data to study the spatial and temporal dynamics of the normalized vegetation index (NDVImax3), elevation gradient (EG) of spring (SOS) and autumn phenology (EOS) during the maximum three months from 1982 to 2015, and found that temperature is not the only control of phenology factor for the autumn phenology.

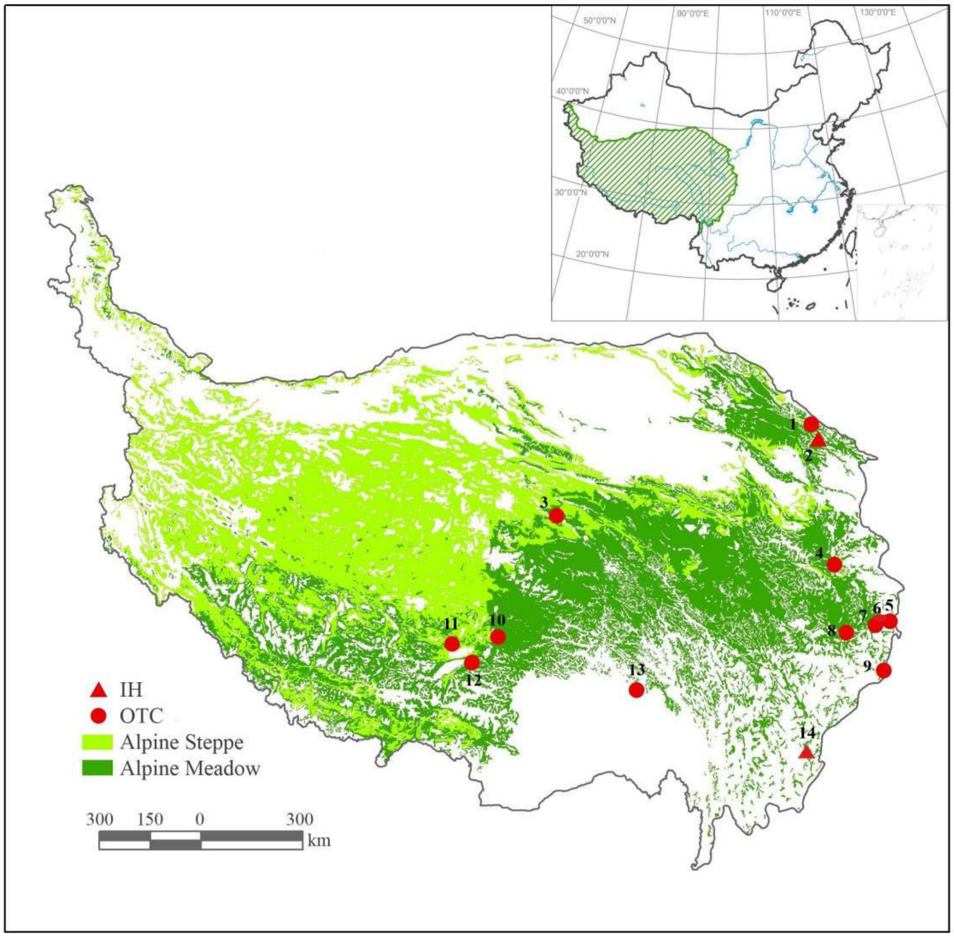

Figure 2: The published on-going warming projects on the Tibetan Plateau. Numbers marked on the map mean the sites described in Table **1**.

In contrast to the field observations, several climate change manipulative experiments using open-top chamber (OTC) method found that warming advanced the onset of growing season and delayed the leaf senescence, and then prolonged the growing season [5,34]. Another overhead infrared heater method to simulate climate warming conducted by Wang *et al*. also observed that warming advanced starting green time and delay ending color time of plant on the Tibetan Plateau [36]. However, Klein *et al*. [28] found that warming sometimes extended, but did not advance, the growing season using open-top chamber (OTC) method. Compared with the researches on the effects of increasing temperature, effects of precipitation changes on plant phenology on the Tibetan Plateau are sparse and uncertainty, which mainly used remote sensing and modeling. Piao *et al*. [37] suggested that increased precipitation could postponed the onset of growing season in alpine meadow in China, which is mostly distributed on the Tibetan Plateau. However, Shen *et al*. [30] indicated that the effects of precipitation on the onset of growing season depended on the study period or stations examined. Increasing pre-season precipitation tends to advance the onset of growing season on the Tibetan Plateau most in areas with lower aridity, where the precipitation exerts a weaker influence. Therefore, further studies based on manipulative experiment will be needed to understand the underlying mechanisms of these responses in future.

3.2. Changes in Plant Productivity and Species Diversity

Rustad *et al*. [38] conducted a meta-analysis of 20 warming experiments, and found that increasing temperature significantly increase aboveground primary productivity (ANPP) by an average of 19%. Similarly, most studies across alpine ecosystems also reported warming prolonged growing season and enhanced plant growth thus induced a significant increase in net primary production on the Tibetan Plateau [5,19,34]. Using OTC method in alpine meadow and swamp

Table 1: Global Change Researches Published from 2000 to 2019 on the Tibetan Plateau

Longitude and Latitude	Site	MAT (°C)	MAP (mm)	Methods	Principal Investigator	References
100º55´E, 37º58´N	1	1	409	OTC and SR	Jianguo Wu	Heng *et al*., 2011
101°12′E, 37°36′N	2	-1.2	486	IH	Jin-Sheng He	Xu *et al*., 2018
101º12´E, 37º36´N	2	-1.7	560	OTC	Julia Klein	Klein *et al*., 2004, 2005, 2007
101º12´E, 37º36´N	2	-1.7	560	IH	Shiping Wang	Luo *et al*., 2009,2010, Lin *et al*., 2011; Duan *et al*., 2012; Wang *et al*., 2012; Shen *et al*., 2013; Wang *et al*., 2014a; Wang *et al*., 2014b; Jing *et al*., 2014; Lin *et al*., 2015
101º12´E, 37º36´N	2	-1.7	560	SR	Zhenxi Shen	Shen *et al*., 2002
92º53´E, 34º43´N	3	-5.3	269.7	OTC	Genxu Wang	Li *et al*., 2011a; Li *et al*., 2011b; Yang *et al*., 2011
92º53´E, 34º43´N	3	-5.3	269.7	OTC	Qing-Bai Wu	Wang and Wu, 2010
100º26´-103º43´E, 34º17´- 34º25´N	4	*	*	OTC	Wei Liu	Zhao *et al*., 2006
104º01´E, 32º59´N	5	2-4	850	OTC	Kai-Yun Wang	Xu *et al*., 2009
103°40′E, 32°59′N	6	4.8	693.2	OTC	Qing Liu	Ma *et al*., 2018, 2019
103º33´E, 32º51´N	7	2.8	718	OTC and SR	Ning Wu	Shi *et al*., 2012
103º33´E, 32º51´N	7	2.8	718	OTC	Ning Wu	Shi *et al*., 2008, Wang *et al*., 2011
102º33´E, 32º48´N	8	8.9	920	OTC	Shucun Sun	Li *et al*., 2011a
103º53´E, 31º41´N	8	8.9	920	IH	Qing Liu	Liu *et al*., 2011
102º35´E, 31º35´N	8	8.9	920	OTC	Qing Liu	Xu *et al*., 2010a, Xu *et al*., 2010b
102º33´E, 32º48´N	8	8.9	920	SR	Shucun Sun	Wu *et al*., 2011a
103º54´E, 31º41´N	9	8.6	919.5	OTC	Kai-Yun Wang	Wu *et al*., 2007
92°00.921'E, 31°38.513'N	10	-1.16	430	OTC	Yangjian Zhang	Jiang *et al*.,2017
88º42´E, 30º57´N	11	0	300	OTC	Xiaodan Wang	Lu *et al*., 2013
91º03´-91º04´E, 30º30´-30º32´N	12	1.3	477	OTC	Zhenxi Shen	Fu *et al*., 2012; Yu *et al*., 2014; Fu *et al*., 2015, Shen *et al*., 2015
91°04′E, 30°30′N	12	1.3	477	OTC	Ning Zong, Peili Shi	Zong *et al*., 2018
91°04′E, 30°30′N	12	1.83	476.03	OTC	Zhenxi Shen	Wang *et al*., 2017
91º41´-100º58´E, 30º27´-30º35´N	13	1.8	*	OTC	Yu-Hong Zhao	Zhao and Wei, 2010
101º30´-102º15´E, 29º20´-30º20´N	14	3.8	1940	IH	Genxu Wang	Yang *et al*., 2013

OTC = Open top chamber; SR = Simulated rainfall; IH =Infrared heater.

meadow ecosystems, Li *et al*. [34] observed that warming significantly increased aboveground plant and root biomass as results of increasing the plant growth or prolonging the growing season, or increasing nutrient availability. Consistent with a meta-analysis of 13 sites by Arft *et al*. [39], increased coverage of graminoids, legumes and ANPP of the community were demonstrated in an alpine meadow on the Tibetan Plateau by Wang *et al*. [19]. However, Klein *et al*. [14,28] found opposite results in the same alpine meadow using an OTC warming experiment. They observed that a decrease of graminoids and a significantly decrease of ANPP due to the contribution of the graminoids to the ANPP of the community. A recent warming experiment on alpine meadows in the northern Tibetan Plateau pointed out that the dryness caused by warming will weaken its impact on vegetation indices and biomass production [40]. A temperature and precipitation control experiment in the alpine grassland in the northeast of the Qinghai-Tibet Plateau confirmed that climate warming did not increase plant biomass but increased its nutrient content, while increasing precipitation significantly increased plant biomass [41].

Table 2: Major Global Change Findings on the Tibetan Plateau

Methods	Years	Spring Phenology	Autumn Phenology	Plant Productivity	Plant Diversity	Greenhouse Gas Emission	Changes in SOC	Other Ecosystem C Dynamics	References
IH	5	advanced	delayed	increased	n.s but varied with year	did not ER; increased N_2O flux during growing season and deceased during non-growing	increased	increased decomposition rate, DOC	Luo *et al*., 2009, Lin *et al*., 2011, Rui *et al*., 2011, Rui *et al*., 2012, Wang *et al*.,2012
IH and SR	3	-	n.s	-	-	-	-	-	Xu *et al*., 2018
OTC	4	n.s	n.s	decreased	decreased	-	-	decreased decomposition rate	Klein *et al*., 2004, 2005, 2007
OTC	1	-	-	-	-	increased ER	-	-	Bai *et al*., 2011
OTC	1	advanced	delayed	increased	-	-	-	-	Xu *et al*., 2009
OTC	3	-	-	increased	-	-	-	-	Li *et al*., 2011b
OTC	1	-	-	-	-	-	-	tended to decrease microbial biomass (MB)	Fu *et al*., 2012
OTC	1	-	-	-	-	increased ER	-	-	Ma *et al*., 2018
OTC	1	-	-	increased	increased	-	-	-	Jiang *et al*., 2017
OTC	1	-	-	n.s	n.s	increased ER	-	increased soil MB	Shi *et al*., 2008, Shi *et al*., 2012
OTC	1	-	-	-	-	Increased ER	n.s.	reduced labile C, but did not affect MB	Xu *et al*., 2010b
Field observation	3	advanced	-	increased	-	n.s	-	depending on the magnitude of temperature	Kato *et al*., 2006, Saito *et al*., 2009
Large-scale survey	24	-	-	-	-	-	n.s	-	Yang *et al*., 2008, 2009, 2010
Remote sensing and modeling	18	advanced	-	increased	-	-	increased	-	Piao *et al*., 2006a,b
Modeling	24	advanced from 1982-1999; delayed from 1999-2006	-	increased	-	increased SR	increased	-	Piao *et al*., 2011
Modeling	55	n.s from 1960-1981; advanced from 1982-2014	n.s from 1960-1981; delayed from 1982-2014	-	-	-	-	-	Yang *et al*., 2017
Remote sensing and modeling	42	-	-	-	-	-	decreased	-	Zhang *et al*., 2007

(Table 2): contd….

Methods	Years	Spring Phenology	Autumn Phenology	Plant Productivity	Plant Diversity	Greenhouse Gas Emission	Changes in SOC	Other Ecosystem C Dynamics	References
Field-sampling,Remote sensing and modeling	5	-	-	-	-	-	decreased	-	Zhao *et al*., 2018
Remote sensing and modeling	24	delayed	advanced	-	-	-	-	-	Yu *et al*., 2010

n.s. = No significantly.

Beyond these, inconsistent with previous studies across tundra ecosystems that warming causes about ~30% species loss [39,42]. And on the Tibetan Plateau, the OTC warming experiment conducted by Klein *et al*. [14] observed that warming caused dramatic declines in plant species diversity. However Wang *et al*. [19] found that warming did not significantly affect plant species richness, but the effect of warming on plant species richness varied with the year. This difference between Klein *et al*. [14] and Wang *et al*. [19] is probably due to the different warming patterns between the OTC and infrared heater system. In addition, the responses of plants to climate changes were relatively slow and often varied with experiment years [19,39]; thus, to better understand the effect of increasing temperature on plant productivity and diversity, long-term continuous observation is needed [12,43].

3.3. Exchanges in Ecosystem C Balance

Temperature and precipitation are key drivers of ecosystem processes, as demonstrated by a number of climate change experiments [44-46]. It is certain that changes in temperature and precipitation have altered ecosystem C dynamics, and therefore will likely feedback to ongoing climate change [43,47-48]. Numerous of climate change studies focused on alpine ecosystem C dynamics since the Tibetan Plateau is considered to be one of the world's most sensitive areas and extensive alpine meadow on the Plateau may play an important role in the regional C balance [6,15,50-52]. One example is an integrated study of the effect of warming on ecosystem C dynamics in the Haibei *Kobresia* alpine meadow conducted by Wang *et al.* [50]. Observations of alpine meadow ecosystem CO_2 fluxes revealed that the ecosystem respiration was mainly controlled by soil temperature rather than soil moisture in the alpine meadow, however, the inter-annual variations in ecosystem respiration were strongly related to precipitation [53]. In the same experiment platform during the same period, some interesting decomposition rate and soil studies have partly explained this phenomenon. Warming increased decomposition rate and dissolve organic carbon concentration in soil solution was found by Luo *et al*. [16,50]. In addition, Rui *et al*. [54-55] observed that warming increased various C and N pools including microbial C, N and soil organic N, meanwhile the effects of warming can be controlled by soil moisture. However, short-term observation of experimental warming effects in alpine meadow using OTC methods indicated that warming tended to decrease microbial biomass, which may be attributed to warming-induced decline in soil water content [56], and the combined effects of warming and drying decreased soil microbial biomass and CO_2 emission rate [52]. A recent research pointed out that experimental warming did not significantly affect the microbial biomass carbon concentration of rhizosphere soil, but significantly affected the microbial biomass carbon concentration of bulk soil, and its degree of influence changed with the growth season [57]. Through warming experiments, Ma *et al*. [58] confirmed that climate warming will increase the heterotrophic respiration and rhizosphere respiration of the Tibetan Plateau, thereby stimulating more carbon emissions from the soil to the atmosphere.

Among the studies of climate change on the Tibetan Plateau, warming manipulative experiment have also demonstrated that winter dynamics have been shown to be particularly important for soil-atmosphere fluxes of greenhouse gases [59]. In addition to climate change manipulative experiments, Saito *et al*. [60] used eddy covariance measurements to study the relationship between net ecosystem CO_2 exchange (NEE) and environmental variables and found that the effect of increasing temperature on NEE could be categorized into no change, increase and decrease depending on the changes in soil temperature at 5 cm depth.

3.4. Changes in Soil Organic Carbon

Starting in 2001, a large-scale survey on soil organic carbon stocks in 405 profiles collected from 135 sites across the Tibetan Plateau was conducted to estimate storage and spatial patterns of soil organic carbon (SOC) in the alpine grasslands [61-62]. This large spatial scale survey, combined with a satellite-based dataset of enhanced vegetation index, showed that topsoil C stocks in the Tibetan Plateau grasslands did not change significantly over the past 20 years. This is inconsistent with the results of regional modeling studies [63], which suggested that extended growing season and enhanced plant growth induced by increasing temperature may result in an increase of organic C inputs to soil. And based on bioclimatic data provided by the IPCC5, Zhao et.al proposed that the total SOC will decrease in the case of global warming [27]. However, Wu *et al*. [51] found that it was root turnover but not rhizodeposition that controlled C flow into soil through plant roots in an alpine meadow on the Tibetan Plateau. Due to the time, little research has been done about how field manipulations of temperature and precipitation as independent or combined factors affect SOC in Tibetan Plateau.

Currently, it is difficult to find consistent trends of plant growth and ecosystem C balance against the on-going climate change in Tibetan Plateau, because (1) there is a small number of global change experiments that conducted in Tibetan Plateau and (2) the lack of precipitation changes and the combined temperature and precipitation manipulations experiments in natural ecosystem in Tibetan Plateau. In addition, the lack of research on the response of the underground part of the Tibetan Plateau ecosystem to climate change has led to a lack of knowledge about the mechanism of ecosystem carbon balance in response to climate change. In the study of the impact of climate change on plants, climate variables cannot be considered solely, and various factors and their connections should be weighed and considered. For example, the grassland ecosystem along the western coast of California can better simulate primary productivity only by establishing a four-dimensional "temperature-precipitation-CO_2-nitrogen" spatial model [64]. To better understand the mechanism of plant growth responses to climate change and the direction and magnitude of ecosystem C balance responses to climate change, the effects of fluctuating temperature and precipitation as well as the combination of temperature and precipitation should be examined on the Tibetan Plateau [46].

4. SUMMARY

In this paper, we have reviewed previous reports on climate changes of Tibetan Plateau and analyzed the observed climate changes on the Tibetan Plateau between 1971 and 2010. We found that Tibetan Plateau is actually experiencing climate warming especially in winter, and precipitation changes both spatially and temporally inconsistent. However, as we have discussed above, the global change researches conducted are non-systematic and limited. It is difficult to find a consistent trend of plant growth and ecosystem C balance against the on-going climate changes on the Tibetan Plateau. Temperature-precipitation manipulative experiments can be our useful approach to understand and predict the possible response of alpine ecosystem to future climate changes.

On the basis of the analysis of the interesting findings of plant growth and ecosystem processes response to climate changes on the Tibetan Plateau, for future global change manipulative experiments conducted on the Tibetan Plateau, we recommend:

1. Conduct more manipulative experiments with combined temperature and precipitation factors. Because of big seasonal variation of climate change on the Tibetan Plateau, these experiments should not only consider the amplitude of temperature and precipitation, but also the seasonality.
2. Identify how climate change affects plant growth processes, both at the scale of individual plant and community. In addition to plant phenology, used both aboveground and belowground biomass and productivity to estimate responses of plant growth to climate change.
3. Provide the systematic variations and potential mechanisms of ecosystem response to climate changes. Through long-term research, understanding how temperature increase and changes in precipitation affect plant allocate C among respiration, storage and transfer can help us to predict how the ecosystem C balance response to climate change and potential feedback to climate change. This will greatly help us take measures to increase carbon sequestration and mitigate climate change on the Tibetan Plateau.

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