Research Article

Responses of Ecosystem CO$_2$ Fluxes to Short-Term Experimental Warming and Nitrogen Enrichment in an Alpine Meadow, Northern Tibet Plateau

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Over the past decades, the Tibetan Plateau has experienced pronounced warming, yet the extent to which warming will affect alpine ecosystems depends on how warming interacts with other influential global change factors, such as nitrogen (N) deposition. A long-term warming and N manipulation experiment was established to investigate the interactive effects of warming and N deposition on alpine meadow. Open-top chambers were used to simulate warming. N addition, warming, N addition × warming, and a control were set up. In OTCs, daytime air and soil temperature were warmed by 2.0°C and 1.6°C above ambient conditions, but soil moisture was decreased by 4.95 m$^3$ m$^{-3}$. N addition enhanced ecosystem respiration (Reco); nevertheless, warming significantly decreased Reco. The decline of Reco resulting from warming was cancelled out by N addition in late growing season. Our results suggested that N addition enhanced Reco by increasing soil N availability and plant production, whereas warming decreased Reco through lowering soil moisture, soil N supply potential, and suppression of plant activity. Furthermore, season-specific responses of Reco indicated that warming and N deposition caused by future global change may have complicated influence on carbon cycles in alpine ecosystems.

1. Introduction

Over the past 50 years, the Tibetan Plateau has experienced pronounced warming [1–3]. By the end of 21st century, the magnitude of mean global temperature is projected to increase by 1.8 to 4.0°C and alpine regions are believed to be exposed to an even higher rate of warming than mean global level [2, 4]. Moreover, alpine ecosystems might be more sensitive because plant growth is often accustomed to low temperature environment [5], and soil respiration is more sensitive to warming at lower temperature [6]. In addition to the direct effects of climate warming on ecosystem productivity due to an extended growing season, warming may alter productivity indirectly by influencing soil N dynamics [7]. Increased rates of N mineralization driven by climate warming may improve plant N availability and could stimulate plant growth in N-limited systems, provided water is not limiting [8, 9]. However, increased N mineralization over winter at a time when plant roots are largely inactive, coupled with an increased frequency of soil freeze-thaw cycles, may increase the possibility of soil N leaching losses and thus affect plant productivity and soil C dynamic in the following growing season due to N limitations of alpine ecosystems [10, 11]. Better understanding of the response of ecosystem CO$_2$ flux to global warming, increasing nitrogen deposition, and their interactions is crucial to project carbon cycling in the future global change scenarios.
The extent to which increased warming will drive changes in plant productivity and ecosystem C flux over the next century will depend on how climate warming interacts with other influential global change factors, such as N deposition, to affect the N retention of ecosystems [12, 13]. Generally, N deposition can increase productivity and biomass accumulation in the short term [14] because alpine ecosystems are primarily N limited caused by low temperature [15, 16]. In addition, N fertilization has led to small, initial increases in soil CO₂ efflux but has generally suppressed it in chronically amended plots [17–19]. Likewise, N additions have initially increased N mineralization, but elevated rates of N cycling have either returned to control levels [20, 21] or declined in the long run [22]. Thus when climate warming and N deposition occur separately, they appear to have opposite effects on soil C and N dynamics, with warming causing long-term soil C losses and high N turnover, but N deposition resulting in soil C gain and low rates of N cycling. However, few studies have explored the interactive effects of climate warming and N deposition on plant productivity and ecosystem C dynamics, especially in N-limited alpine ecosystems.

Ecosystem respiration is primarily controlled by soil temperature and soil water content and complex interactions between them [23]. In semiarid and arid regions, soil water content is the main factor regulating plant growth and soil microbial activity [24–26] and subsequently mediates the apparent temperature sensitivity to soil temperature [27, 28]. Besides the direct effect on ecosystem respiration by elevating temperature, experimental warming can also indirectly decrease ecosystem CO₂ fluxes by altering (mostly reducing) soil water availability, especially in months with few precipitation events in semiarid and arid regions.

In this study, we examined the interactive effects of simulated climate warming and N deposition on ecosystem CO₂ efflux, soil N dynamic, and plant productivity in a semiarid alpine meadow on the Tibetan Plateau. We conducted year-round warming treatments by open-top chambers (OTCs) crossed with N enrichment treatments (4 g N m⁻² year⁻¹) in a factorial design. We hypothesize that warming would decrease plant productivity and ecosystem CO₂ efflux, caused by indirect decrease of soil moisture in this semiarid region. We also predicted that N enrichment would counteract the effects caused by simulated warming through increase of water and N availability in late growing season.

2. Materials and Methods

2.1. Site Description. This study was carried out in the grassland station of Damxung County (91°05′ E, 30°51′ N, 4333 m a.s.l) in the south-facing slope of Nyainqentanglha Mountains, north Tibetan Plateau. A detailed site description was introduced in literature [16, 29]. According to observations from 1963 to 2010 at Damxung meteorological station (4288 m a.s.l, ca. 3 km away from our experimental plot), annual mean air temperature increased by 1.6°C while precipitation showed a declining trend from 1963 to 1990 but an increasing trend from 1991 to 2010 [30].

2.2. Experimental Design and Microclimate Monitoring. The field manipulations consisting of warming (year-round warming and control) crossed with two N addition treatments (added N and control) were organized in a randomized block design with five replicates for each of the four treatments. We followed methods of the International Tundra Experiment and applied ten open-top chambers (OTCs), the passive warming device to generate artificially warmed conditions [2, 31] for five controls and five N addition plots. The OTCs, with 100 cm diameter of top opening, 140 cm diameter of bottom, 40 cm in height, and a bottom area of 1.54 m², are made of 3 mm thick polycarbonate plastic. This material has high solar transmittance in visible and ultraviolet wavelengths (about 90%) [32]. In N added plots, we applied a pulse of aqueous ammonium nitrate (NH₄NO₃) at a rate of 2 g N m⁻² year⁻¹ in early June and early August, respectively. These addition rates are designed to approximate projected increases in atmospheric deposition in this region by the year of 2050 [33]. We set up the warming plots in early July 2010 and synchronously monitored the warming effects on year-round air temperature, soil moisture, and temperature at 5 cm depth by a HOBO weather station (Onset Inc., Bourne, MA, USA) on half-hour frequency. The distance for buffer between each replicate was at least 3 m.

2.3. Measurement of Aboveground and Belowground Biomass. A nondestructive sampling method was used to estimate aboveground biomass [34–36]. Briefly, the average height and cover of vegetation canopy were measured using a 50 cm × 50 cm quadrant divided into twenty-five 5 cm × 5 cm subsquares in each plot on July 01, July 25, August 25, and September 17 in 2012. We also carried out this process in nearby alpine meadow on each sampling date by measuring mean height and cover of vegetation canopy, harvesting, oven-drying, and weighing the vegetation materials. The equation that was used to simulate the relationship between aboveground biomass (AGB) and vegetation height (H) and cover (C) is AGB = 0.269 + 3.466 C + 0.752 H (R² = 0.658, P < 0.001, and N = 80). We also used a soil-drill sampler (5 cm in diameter) to take 0–10 cm and 10–20 cm soil samples in mid-August and these root samples were immediately washed, separated, oven-dried at 65°C for 48 h, and weighed.

2.4. Soil Net N Mineralization. Soil net N mineralization was measured using the buried soil core technique employed by [37, 38]. The concentrations of extractable NO₃⁻-N and NH₄⁺-N were compared in initial and incubated soil cores in situ for approximately three weeks. While taking one soil sample core for immediate analysis, another three intact soil cores were taken out, placed into a polyvinyl chloride (PVC) collar (5 cm in diameter and 12 cm in height) at a depth of 10 cm, resituated into the soil, and sealed with plastic wraps which can prevent N deposition by rainfall and maintain enough ventilation [39]. Every three weeks after soil sampling, the incubated cores were taken out from soil holes on July 25, August 16, and September 6, 2012, respectively. Soils in the cores were immediately passed through a 2 mm sieve to remove roots, gravel, and stones. Within 48 hours
from each soil sampling, \( \text{NO}_3^-\text{-N and NH}_4^+\text{-N of initial}
\) and incubated cores were extracted using 2 mol L\(^{-1}\) KCl and
filtered and analyzed on a continuous flow analyzer (AA3,
SEAL Analytical, Germany). The differences of inorganic N
(mg kg\(^{-1}\), total summary of \( \text{NO}_3^-\text{-N and NH}_4^+\text{-N} \)) between
the initial and incubated soil cores divided by incubated
time (day) were used to estimate the rate of inorganic N
mineralization (mg kg\(^{-1}\) d\(^{-1}\)).

2.5. Measurement of Ecosystem Respiration. During the growing
season, ecosystem respiration was measured from June
to September in 2012 by a portable soil CO\(_2\) flux system
(LI-8100, LI-COR Biosciences, Lincoln, NE, USA). Briefly, PVC
chambers with 20 cm in diameter and 5 cm in height were
inserted into the soil to a depth of 3 cm one month before
our measuring process and intact plant was kept in PVC
chambers. Ecosystem respiration was measured at 3-hour
intervals in July 22–23 and August 21–22 from 18:00 p.m.
to 18:00 p.m. (local time) in the next day to achieve the diurnal
variation pattern. Nine cycles of data were obtained in each
measurement date. In addition, CO\(_2\) fluxes between 09:00
and 11:00 a.m. (local time) were also measured every 10 days
to represent daily mean flux because the CO\(_2\) fluxes in these
periods are equal to daily averages according to previous
studies in this site in the growing season [16, 40]. In all,
ten daily average CO\(_2\) fluxes were obtained throughout the
growing season.

2.6. Statistical Analysis. To examine the effects of warming on
temperature sensitivity of ecosystem CO\(_2\) flux, exponential
regression models \( R = ae^{bT} \) were used, in which \( R \) is the
ecosystem CO\(_2\) flux, \( T \) is the soil or air temperature,
coefficient \( a \) is the ecosystem CO\(_2\) flux when temperature is
zero, and coefficient \( b \) represents the temperature sensitivity
of ecosystem CO\(_2\) flux. \( Q_{10} \) value, calculated as \( R_{T+10}/R_{T} \),
where \( R_{T} \) and \( R_{T+10} \) are ecosystem CO\(_2\) fluxes at temper-
ature \( T \) and \( T + 10 \), respectively, was used to evaluate the
dependence of ecosystem CO\(_2\) flux on temperature on
diurnal scales. Regression analyses were performed to test the
dependence of ecosystem CO\(_2\) flux on soil water content, soil
temperature, plant aboveground biomass, and soil inorganic
N content at seasonal scales. Repeated-measure ANOVA
was applied to assess the effects of warming and N addition on
ecosystem CO\(_2\) flux. One-way ANOVA analyses followed
by Tukey multiple comparison were used to examine the
differences in monthly average ecosystem CO\(_2\) flux, plant
biomass, soil inorganic N content and net mineralization
rate among treatments during growing season. Before each
analysis, all data were tested for homogeneity. If not, they
were In-transformed before analysis. Significance level was
95% confidence interval. All the analyses were performed in
SPSS 16.0 (SPSS for Windows, Version 16.0, Chicago, USA).

3. Results

3.1. Warming Effects on Microclimate. Simulated warming
significantly resulted in an average increase of 2.0\(^\circ\)C day-
time air and 1.6\(^\circ\)C soil temperature compared with ambient
conditions during growing season (from June to September;
Figure 1(a); \( P < 0.05 \)). However, warming was not significant
in nighttime air temperature and increased by only 0.6\(^\circ\)C in
soil temperature (Figure 1(b); \( P > 0.05 \)). On the contrary,
soil water content in day and night was indiscriminately
decreased by 4.95 m\(^3\) m\(^{-3}\) resulting from simulated warming
(Figure 1(c)), causing a warmer and dryer condition in
the OTCs. Correlation analysis showed that the decrease
of soil water availability during daytime was marginally
correlative with the increase of soil temperature (\( P = 0.096 \)).
Precipitation was 312.7 mm during growing season in 2012,
mainly concentrating in July and August (49% and 24% of
the total, resp.) (Figure 1(c)).

3.2. Diurnal and Seasonal Variations of Ecosystem Respiration.
Ecosystem CO\(_2\) fluxes showed diurnal variations with peak
values at 15:00 p.m. and minimum values at 03:00~06:00 a.m.
in two measuring dates in growing season (Figure 2). More-
over, ecosystem CO\(_2\) fluxes also showed seasonal variations
with peak values in mid-August (Figure 3).

N addition had no effects on ecosystem CO\(_2\) fluxes in June
and July but significantly increased them by 16% and 21% in
August and September (Figures 2 and 3; Table 1; \( P < 0.05 \)),
respectively. Warming significantly decreased ecosystem CO\(_2\)
fluxes by 44% and 23% in June and July (Figure 3; \( P < 0.05 \)),
respectively, while the effects were not pronounced in
September (Figure 3; \( P > 0.05 \)). N addition and warming
significantly decreased ecosystem CO\(_2\) fluxes by 31% in June
(Figure 3; \( P < 0.05 \)), but the effects were not pronounced
compared with control treatment in the following period,
indicating that N enrichment cancelled out the decline of
warming effects on ecosystem CO\(_2\) fluxes in peak growing
season.

3.3. Plant Production. N addition significantly increased
aboveground and belowground biomass (Figure 4). For
example, N addition increased aboveground biomass by 18%
(Figure 4(a); Table 1; \( P < 0.05 \)) and belowground biomass
by 55% (Figure 4(b); \( P < 0.01 \)), respectively, in August. On
the contrary, warming significantly decreased aboveground
biomass by 38% (Figure 4(a); Table 1; \( P < 0.05 \)) in August.
N addition and warming treatments decreased aboveground
biomass in early growing season but this trend reversed in
late growing season (Figure 4(a)). For example, aboveground
biomass decreased by 41% (\( P < 0.05 \)) in July while increasing
by 29% (Figure 4(a); \( P < 0.05 \)) in September under N
addition and warming treatments.

3.4. Soil Inorganic N Content and Mineralization Rate. N
addition enhanced soil mineral N content and mineralization
rate in early growing season (Figure 5; \( P < 0.05 \)) while warming
decreased soil mineral N content in this season. In middle
growing season, the rate of soil microbial immobilization was
higher than mineralization rate (Figure 5(b)). However, N
addition combined with warming significantly increased soil
mineral N content by 4.5 times and mineralization rate by 12.9
times at the end of growing season (Figure 5; \( P < 0.01 \)).
3.5. Controlling Factors. Linear regression analysis showed that seasonal variations of ecosystem CO₂ flux were negatively correlated with air temperature and soil temperature, whereas ecosystem CO₂ flux was positively correlated with soil water content at the depth of 5 cm (Figures 6(A)–(C)), especially in warming treatments, indicating that decline of soil water content and increase of soil and air temperature in warming treatments accounted for the decline of ecosystem CO₂ flux at seasonal scale. However, diurnal variations of ecosystem CO₂ flux were exponentially correlated with air temperature and soil temperature. Air temperature and soil temperature could explain 47.2%–47.7% and 26.6%–30.1% of
Warming effects decreased the temperature sensitivity \( (Q_{10}) \) of CO\(_2\) fluxes, which was 1.70 response to air temperature and 1.77 to soil temperature in warming treatments compared with 2.14 to air temperature and 2.59 to soil temperature (Figure 6, \( P < 0.05 \)), respectively.

Ecosystem CO\(_2\) fluxes exhibited significant correlation with aboveground biomass and soil inorganic N content (Figure 7), indicating that plant production and soil N availability were critical factors regulating seasonal variations of ecosystem CO\(_2\) fluxes. More pronounced above-mentioned correlations were found in warming plots than the ambient plots, illustrating that the decline of biomass and soil N availability resulting from warming accounted for the decrease of ecosystem CO\(_2\) fluxes in warming plots.

4. Discussion

Our results showed that short-term N addition enhanced plant biomass and ecosystem CO\(_2\) flux, but the increase of CO\(_2\) flux was significant only in late growing season. On the contrary, warming decreased CO\(_2\) flux and plant biomass over the whole growing season, with most pronounced effects in June and July. N addition offset the decrease of soil respiration and plant biomass resulting from warming. The above results corroborate our hypotheses and highlight the dampening effects of reduced soil water conditions on N availability and ecosystem CO\(_2\) fluxes caused by indirect effect of warming and additive effects of nitrogen and warming in late growing season.

4.1. Warming Effects. Warming significantly reduced aboveground biomass (Figure 4) and ecosystem respiration (Figure 3), and these effects were pronounced in early growing season. Generally, warming may increase plant N availability by enhancing rates of N mineralization, which, coupled with an extended growing season, could promote plant growth in N-limited ecosystems, provided soil water is not limiting [8, 9]. However, early growing season in present study site is the time that precipitation events are generally rare. The reduction of soil water content in warming treatments suppressed the potentially positive effects of warming on plant growth and C fluxes. In addition, warming over nongrowing season, combined with microbial C limitation at this time [41, 42], could enhance N mineralization. But plant activities are largely dormant and soil microorganisms are mostly absent for N immobilization; thus winter warming may cause large amount of N leaching or trace gases emission during increased frequency of soil freeze-thaw cycles [43–45]. In our study, soil mineral N content in warming plots was very low in early growing season possibly due to large loss of N during winter warming (Figure 5). This may render negative effect on plant growth. As plant N uptake in early growing season was of great importance for plant productivity in the following season due to N limitations of alpine ecosystems [46], thus, warming decreased ecosystem CO\(_2\) fluxes through the suppression of production productivity as ecosystem respiration in growing season may primarily depend on the utility of recent plant photosynthates [37, 47].

In the growing season, the passive warming by OTCs significantly enhanced daytime soil and air temperature while decreasing soil water content (Figure 1), which may have great impacts on plant community and CO\(_2\) efflux in early growing season when rainfall events are rare. In semiarid region, soil moisture is a key environmental factor controlling season variations [16] and large-scale pattern [48] of ecosystem CO\(_2\) flux. The decline of soil water availability caused by warming directly suppressed ecosystem CO\(_2\) fluxes. In addition, soil microbial carbon and N were also reduced by warming because warming may inhibit the activities of soil microorganisms and substrate supply for its reproduction due to the decline of soil water availability [2, 49]. In addition, the decline of soil N availability in OTCs also accounted for the decrease of ecosystem CO\(_2\) fluxes, as N availability in soil may directly affect soil microbial activities.

4.2. Nitrogen Enrichment Effects. N enrichment treatment significantly enhanced above- and belowground biomass in peak and late growing seasons (Figure 4), accompanied with stimulation of ecosystem CO\(_2\) fluxes (Figure 3). Generally, soil N mineralization is very slow due to high altitude and low temperature on the Tibetan Plateau, leading to the limitation of N availability on plant production [16, 50]. Exogenous N input could speedily enhance plant N availability in soil, resulting in the increase of N content in plant leaves and promotion of photosynthetic capacity [51]. Our results showed that N enrichment also accelerated soil net N mineralization in early growing season (Figure 5), which could stimulate the decomposition of soil organic matter [52] and in turn increase soil N content and subsequently promote plant production [38]. Increased plant productivity means more plant growth and maintenance respiration [23] and more plant photosynthates supply to soil microorganisms [26, 53]. Therefore, the increase of plant productivity caused by N enrichment was an important source for the increase of ecosystem CO\(_2\) fluxes.
Figure 4: Seasonal variations of plant aboveground and belowground biomass over growing season under different treatments in alpine meadow in 2012. See Figure 2 for the abbreviations of treatments.

Figure 5: Seasonal variations of soil inorganic N (a) and soil net N mineralization (b) over growing season under different treatments in alpine meadow in 2012. See Figure 2 for the abbreviations of treatments.

Table 1: Repeated-measure analyses of variance (ANOVAs) for ecosystem respiration (Reco), aboveground biomass (AGB), soil inorganic N content, and mineralization rate in 2012. $F$ and $P$ values represent $F$ value of ANOVA results and statistical significance, respectively. The significant level is $P < 0.05$.

<table>
<thead>
<tr>
<th>Model</th>
<th>Reco F</th>
<th>Reco P</th>
<th>AGB F</th>
<th>AGB P</th>
<th>Soil inorganic N content F</th>
<th>Soil inorganic N content P</th>
<th>Soil N mineralization rate F</th>
<th>Soil N mineralization rate P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warming (W)</td>
<td>8.063</td>
<td><strong>0.015</strong></td>
<td>62.290</td>
<td>&lt;0.001</td>
<td>0.004</td>
<td>0.948</td>
<td>32.108</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>3.911</td>
<td>0.071</td>
<td>53.157</td>
<td>&lt;0.001</td>
<td>30.078</td>
<td><strong>0.001</strong></td>
<td>33.617</td>
<td><strong>0.001</strong></td>
</tr>
<tr>
<td>W × N</td>
<td>0.034</td>
<td>0.875</td>
<td>2.710</td>
<td>0.126</td>
<td>3.684</td>
<td><strong>0.034</strong></td>
<td>10.375</td>
<td><strong>0.001</strong></td>
</tr>
<tr>
<td>Date (D)</td>
<td>31.208</td>
<td><strong>0.000</strong></td>
<td>147.502</td>
<td>&lt;0.001</td>
<td>60.798</td>
<td><strong>0.001</strong></td>
<td>494.949</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D × W</td>
<td>0.945</td>
<td>0.414</td>
<td>11.565</td>
<td>&lt;0.001</td>
<td>15.222</td>
<td><strong>0.001</strong></td>
<td>251.430</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D × N</td>
<td>0.892</td>
<td>0.436</td>
<td>11.300</td>
<td>&lt;0.001</td>
<td>13.242</td>
<td><strong>0.001</strong></td>
<td>54.143</td>
<td><strong>0.001</strong></td>
</tr>
<tr>
<td>D × W × N</td>
<td>0.268</td>
<td>0.801</td>
<td>4.614</td>
<td><strong>0.023</strong></td>
<td>62.886</td>
<td>&lt;0.001</td>
<td>46.345</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Plant aboveground biomass in N addition combined with warming treatment was significantly higher than that in warming treatments (Figure 4), indicating that exogenous N input compensated the effects of low soil N content and soil water availability on plant production and soil microbial activities caused by warming, especially in late growing seasons (Figure 5). In line with another study in a temperate old field during exceptionally dry summer [54], plant aboveground biomass under N addition treatments had no significant difference with that under N addition combined with warming treatments in this semiarid alpine ecosystem (Figure 4), demonstrating that precipitation distribution appears to play a key role in modulating the effects of climate warming and enhanced N deposition [54].

4.3. Factors Regulating Ecosystem CO$_2$ Flux. Soil temperature is the main environmental factor driving changes in respiration rate [55]. The positive relationship between CO$_2$ flux and...
soil temperature has been included in many models related to carbon cycling [56, 57]. Our results demonstrated that soil and air temperature were critical factors that exponentially correlated with ecosystem respiration which could explain 26.6% and 47.2% of diel variations of ecosystem respiration under warming treatments and 30.1% and 47.7% in ambient treatments ($P < 0.01$). We found temperature sensitivity of CO$_2$ efflux ($Q_{10}$) by Van’t Hoff’s equation [58] was decreased with simulated warming, which is coincident with other researches [59], suggesting that plant growth and diurnal variations of ecosystem CO$_2$ fluxes in high altitude and cold-climate ecosystems are mainly limited by low temperature [2]. On the contrary, at the seasonal scales it was negatively correlated with air and soil temperature but positively correlated with soil moisture (Figure 6) because the soil water availability plays decisive role in affecting plant productivity [24–26], soil microbial activity [60, 61], and consequently the response of ecosystem CO$_2$ flux to temperature [62] in this semiarid region. In addition, along with plant growth, photosynthetic capacity increases and supplies more substrates to belowground biological processes, which is confirmed by positive correlation between ecosystem CO$_2$ flux and aboveground biomass (Figure 7(a)). Thus the relationship between ecosystem CO$_2$ flux and temperature was confounded by soil water availability and plant productivity, which is consistent with another study results in this area [16]. Besides, ecosystem CO$_2$ flux was positively correlated with soil inorganic N content under warming treatments ($P < 0.01$) but not in ambient conditions (Figure 7(b); $P > 0.05$), indicating that the decrease of soil inorganic N content under simulated warming treatments imposed restrictions on soil respiration.

5. Conclusions

The present study revealed that short-term N addition enhanced ecosystem CO$_2$ flux by increasing soil N availability and plant production, whereas warming decreased it through reducing soil moisture and soil N supply and subsequently suppressed plant activities and N enrichment could make up for this reduction to some extent. In addition, we found that the alteration of soil water content caused by warming mediated the warming effects on fate of ecosystem C and N cycling. Warming in this semiarid alpine meadow ecosystem has consequences for soil N cycles and ecosystem C fluxes that differentiate from other ecosystems.
Based on our results, we propose a conceptual diagram of how experimental warming and N addition affect C and N cycling in semiarid alpine meadow ecosystem (Figure 8). Besides the direct effect on plant production, warming alters plant production by decreasing soil water content and increasing inorganic N loss, especially in early growing season when precipitation is rare. The reduction of soil water availability can directly suppress ecosystem CO₂ fluxes and inhibit soil microbial activities and indirectly affect ecosystem C cycling. Furthermore, the decrease of soil water content may have influences on N mineralization and subsequently alter the N supply to plant. Increased precipitation in late growing season has the potential to relieve soil water stress and thus increases ecosystem C fluxes. However, N enrichment can partially offset the decrease of soil N availability directly by exogenous N supply and indirectly through stimulation on soil N mineralization. Coupled with the relief of soil water limitation and low N demand for plants in late growing season, net N mineralization is relatively high. This conceptual diagram is primarily based on the observation of C and N cycling in this semiarid alpine meadow. For better understanding of these processes, we need long-term monitoring of the seasonal and interannual response of plant productivity and ecosystem CO₂ fluxes to precipitation pattern and in-depth mechanistic processes (i.e., microbial C and N content as well as its activities and community composition) that drive ecosystem C and N cycling.

Conflict of Interests
The authors declare that there is no conflict of interests regarding the publication of this paper.

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