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Experimental warming triggers divergent ecosystem multifunctionality responses across Tibetan montane grasslands

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Abstract

Aim

Anthropogenic climate warming is profoundly altering the structure, functioning, and multifunctionality of high-elevation grassland ecosystems, especially across the diverse montane grassland communities on the Tibetan Plateau. However, the influences of warming-induced changes on multiple ecological functions of these mountainous grassland ecosystems remain unclear.

Methods

Here, we conducted a manipulative field experiment across a natural elevational gradient (4500–5300 m) to evaluate warming impacts on aboveground (AEMF), belowground (BEMF), and whole-ecosystem multifunctionality (EMF) across three typical mountain grasslands (steppe, meadow, and screes).

Results

This study demonstrated that warming had inconsistent impacts on multiple ecosystem functions across mountainous grasslands, with the EMF, AEMF, and BEMF indexes generally decreasing in water-limited steppe, increasing in temperature-limited screes, and remained unchanging in meadow. The divergence responses of ecosystem multifunctionality indexes to warming across mountain grasslands were highly driven by biodiversity, productivity, and soil carbon. The findings further suggested that warming could have a stronger impact on productivity and carbon sequestration than on biodiversity in Tibetan mountainous grasslands.

Conclusions

Given that these changes can have broad implications for multiple ecosystem functions, future efforts to predict ecosystem responses to climate change should place comparable emphasis on productivity and carbon dynamics as on biodiversity.

Introduction

Grasslands are exceptionally widespread terrestrial ecosystems on Earth, functioning as critical reservoirs of global biodiversity and carbon sinks (Maestre et al. 2012; Yang et al. 2014; Bai et al. 2022). Since the Industrial Revolution, anthropogenic greenhouse gas emissions have elevated atmospheric concentrations to unprecedented levels, resulting in accelerated global climate warming (IPCC, 2021; Kuang et al. 2016). High-elevation ecosystems, such as the diverse mountain grassland communities on the Tibetan Plateau, are uniquely vulnerable to climatic disturbances due to their adaptation to extreme cold and aridity (Schuur et al. 2015). In recent decades, the Plateau undergone dramatic warming (Du et

al. 2025), which is projected to profoundly altering ecosystem functions of mountain grasslands (García et al. 2018). However, the influences of warming on the multiple ecological functions of these montane grassland ecosystems remain poorly understood.

Climate warming can fundamentally restructure grassland ecosystems through alter plant community composition, shifting plant productivity, transforming soil biogeochemical cycles, and modifying microhabitat conditions, with profound impacts on ecosystem functioning (Wu et al. 2024). Extensive research has shown that climate warming exerts complex and often contrasting impacts on critical ecosystem processes and functions in grasslands (Ganjurjav et al. 2016; Hopping et al. 2018; Liang et al. 2024; Ma et al. 2024). For instance, warming can enhance plant diversity in temperate grasslands while suppressing it in alpine ecosystems (Steinbauer et al. 2018; Zhao et al. 2024). This contrast is further evidenced by the divergent effects of warming on soil microbial communities that warming reduces bacterial diversity in temperate soils but elevates it in alpine regions (Yu et al. 2019; Wu et al. 2022). Similarly, soil carbon and nitrogen cycling processes exhibit divergent responses across grassland ecosystems, regulated by local hydrothermal constraints and vegetation types (Liang et al. 2011; Fazlioglu et al. 2021; Wei et al. 2023). These contradictions emphasize that understanding the mechanism of the synergistic effect between biotic and abiotic factors is essential for predicting ecosystem functioning responses to climate warming.

Ecosystem multifunctionality (EMF), which perform diverse ecosystem functions and services simultaneously, has emerged as a key metric to assess the responses of grassland functioning to climate change (Jing et al. 2015; Gao et al. 2025). EMF reflects ecosystem complexity by integrating multiple individual functions, including biodiversity conservation, plant productivity, and soil carbon and nutrient sequestration (Manning et al. 2018). The interactions among species are instrumental in regulating biodiversity -ecosystem function linkages (García et al. 2018; Benkwitt et al. 2020). Warming-induced shifts in plant species composition can affect grassland primary productivity (Liu et al. 2018) and change soil carbon and nutrient cycles (Bjorkman et al. 2018). Microbial diversity is frequently associated with ecosystem functional processes (Chen et al. 2022; Wu et al. 2022), and warming-induced loss of microorganisms can affect the functional capacity of microbial communities (García et al. 2018). The coupling between plants and microorganisms may change with changing biodiversity (Trivedi et al. 2022), leading to variations in aboveground-belowground feedback mechanisms (Zhao et al. 2024).

The Tibetan Plateau hosts among the largest global montane grasslands. A growing body of experimental warming studies have been widely carried out in Tibetan montane grasslands to quantify the effects of warming on individual ecosystem functions and ecosystem multifunctionality (Chen et al. 2024; Wu et al. 2024). Along elevational gradients, water and temperature present different hydrothermal combination patterns, resulting in different montane vegetation communities (Rumpf et al. 2018; Wang et al. 2021). Montane grasslands at higher elevations are primarily constrained by low temperature, whereas water availability becomes the dominant limiting factor at low elevations (Wang et al. 2013; Zhao et al. 2016). These constraints could modulate the effects of warming on individual and multiple

ecosystem functions across elevational gradients in montane grasslands (Zhao et al. 2024). However, it still uncertainty about how warming will affect the ecosystem functions across the diverse montane grassland communities on the Tibetan Plateau.

To address these issues, we examined how experimental warming influences individual and multiple ecosystem functions along an elevational gradient in the montane grasslands of the central Tibetan Plateau. We hypothesized that warming effects on ecosystem functioning would vary among vegetation types, mediated by distinct combinations of plant diversity, productivity, and soil biogeochemical properties. We further hypothesized that warming would have divergent effects on ecosystem functions, exerting positive impacts in temperature limited grasslands and negative impacts in water limited grasslands. Specifically, this study aims to explore: (1) How does warming influence individual and ecosystem multifunctionality of montane grasslands along an elevational gradient? (2) How do responses of above-and belowground ecosystem multifunctionality to climate warming vary across vegetation types? (3) How do climate, vegetation, and soil properties differentially contribute to mediating ecosystem multifunctionality responses to warming?

Materials and Methods

Study sites

The research site is situated in Nyainqentanglha Mountain, Damxung County, Xizang Autonomous Region. This area features a temperate, semi-arid monsoon plateau climate recording mean annual temperature of 1.8°C and mean annual precipitation of 479 mm (Zhao et al. 2016). Along the ascending elevational gradient, temperature declines while precipitation increases. This inverse pattern creates warmer and drier conditions in the low elevations but colder and wetter conditions in the high elevations. Variations in hydrothermal conditions along the slope of Nyainqentanglha Mountain have given rise to distinct vegetation types which exhibit a clear elevational zonation: alpine steppe at low-elevation zones (4400–4600 m), alpine meadow at mid-elevation zones (4600–5200 m), and alpine screes at the uppermost zones (5200–5600 m). In the low-altitude alpine steppe, characterized by relatively higher temperatures and lower rainfall, the dominant species in the plant community are *Stipa purpurea* and *Kobresia pygmaea*. The mid-altitude alpine meadow ecosystem, which is primarily dominated by *Kobresia pygmaea*, exhibits the highest biomass. The high-altitude alpine scree ecosystem is dominated by the cushion plant *Androsace tapete*, a representative species of this extreme environment. The stringent temperature limitations resulted in the lowest species richness and productivity observed in the alpine screes.

Experimental design

In May 2020, we carried out a warming experiment using open-top chambers (OTCs) on the southern slope of Nyainqentanglha Mountain to simulate projected future climate scenarios. The OTCs (0.4m in

height and 1.4m in diameter) increased air temperature by approximately 1.5°C. Along the elevation gradients, three study sites were selected with distinct vegetation types including steppe (4500 m), meadow (4900 m), and screes (5300 m) (Fig. 1). At each of the three sites, a 20 m × 20 m area was fenced to preclude human interference and herbivore grazing. Within each fenced area, six 4 m × 4 m blocks were randomly placed, each containing two paired plots (warming and ambient). At each sampling site, HOBO miniature automatic weather stations were installed to continuously record air temperature, soil temperature, and soil moisture, thereby characterizing the local microclimatic conditions.

Vegetation sampling

Vegetation surveys were carried out during the seasonal biomass maximum in mid-August 2023 across all warming and ambient plots. Within the center of each plot, a 0.5 m × 0.5 m sampling quadrat was set. In total, 36 warming and ambient quadrats across the three sites were investigated. Within each quadrat, plant coverage, height, and aboveground biomass (AGB) were measured and recorded. Species relative importance value (IV) and diversity metrics, including Species richness index (*S*), Shannon-Wiener diversity index (*H*), Evenness index (*E*), and Simpson diversity index (*D*), were subsequently calculated. The IV was determined as the arithmetic mean of relative coverage (RC), relative height (RH), and relative biomass (RB) (Zhao et al. 2023):

$$IV = (RC + RH + RB)/3$$

$$S = R$$

$$H = -\sum P_i (\ln P_i)$$

$$E = H/\ln S$$

$$D = 1 - \sum P_i^2$$

Here, R indicated total species number and P_i denoted the IV of the ith species.

Soil sampling and analysis

At each quadrat, soil was sampled by extracting and combining four cores (0–10 cm depth) with a 3.8 cm diameter auger and subsequently combining them. After removing visible roots and rocks, each mixed soil sample was subsequently divided. One portion was immediately preserved on ice for transport to the laboratory, while the other part was air-dried at room temperature and sieved through a 2 mm mesh. We determined soil organic carbon (SOC) and total nitrogen (TN) concentrations using a Vario EL III analyzer (Elementar, Germany). NO_3^-–N and NH_4^+–N levels were analyzed using an Auto Analyzer (Bran Luebbe, Germany). Particulate organic carbon (POC) and mineral-associated organic

carbon (MAOC) were isolated from the soil by means of a wet-sieving procedure through a 53 μm sieve following chemical dispersion (Díaz-Martínez et al. 2024). The POC/ MAOC (P/M) was used to represent the stability of soil carbon. We selected the Shannon-Wiener index, Chao1 index, and Shannon Evenness to assess fungal and bacterial diversity, abbreviated as F-*H*, F-*Chao*, and F-*E* for fungi, and B-*H*, B-*Chao*, and B-*E* for bacteria, respectively.

Ecosystem multifunctionality

To quantify how multiple ecological functions vary across three mountain grassland types (steppe, meadow, and screes), we computed indices of ecosystem multifunctionality (EMF), aboveground ecosystem multifunctionality index (AEMF), and belowground ecosystem multifunctionality index (BEMF) based on biodiversity, productivity, carbon sequestration, and nitrogen sequestration functions. The AEMF, BEMF, and EMF indexes were calculated as follows (Descombes et al. 2020; Maestre et al. 2012):

$$\mathrm{EMF} = \frac{1}{N} \Sigma_{i=1}^{N} f(x_i)$$

where, *N* represents function count, and $f(x_i)$signifies the standardized observation for function i. Furthermore, we quantified productivity (height, coverage, AGB), biodiversity (*S*, *D*, *H*, *E*, F-*H*, F-*Chao*, F-*E*, B-*H*, B-*Chao*, and B-*E*), soil carbon (SIC, SOC, MAOC, POC, and P/M) and soil nitrogen (STN, NH_4^+–N, and NO_3^-–N) using the same methodology.

We further utilized the relative interaction intensity (*RII*) index to assess the impact of warming on the individual and multiple ecological functions. Warming effects on these functions were evaluated using the relative interaction intensity (RII) index, with $A_{Warming}$ and $A_{Ambient}$ representing respective values from warmed and control treatments:

$$RII = (A_{Warming} - XA_{Ambient})/(A_{Warming} + A_{Ambient})$$

$A_{Warming}$ and $A_{Ambient}$ represent the ecological function values in warming and ambient plots. The value above zero implies a positive effect, whereas the value below zero indicates a negative impact.

Data analysis

We employed a two-way ANOVA to examine the impacts of warming, vegetation type, and their interaction on both individual ecosystem functions and multifunctionality indices. We further evaluated the differences in individual and multiple ecosystem functions of mountain grasslands between ambient and warming conditions. Structural equation model (SEM) evaluated the indirect and direct influences of warming, vegetations, productivity, biodiversity, soil carbon, and soil nitrogen on EMF, AEMF, and BEMF. Model fit was confirmed through RMSEA and χ^2 metrics. AMOS 26 (IBM SPSS, Inc.) was employed for constructing the SEM model. ArcGIS 10.8 (ESRI) was utilized to generate the vegetation map, and SPSS 27.0 (IBM SPSS Software Inc) was used for statistical analysis.

Results

Warming impacts on plant and soil factors

We found that warming significantly reduced the IV value of sedges in meadow community, while increased that of forbs and grasses (Fig. S1). However, in screes, warming led to a decreased importance value of cushion plants and a concurrent increase in sedges and grasses (Fig. S1). Warming decreased plant coverage and AGB in steppe and meadow but exhibited a tendency to enhance these attributes in screes (Fig. 2 and Fig. S2). Plant height increased under warming in meadow and screes, with nonsignificant change observed in steppe (Fig. 2b and Fig. S2b). Plant diversity in meadow and screes rather than steppe showed an increasing trend under warming. (Fig. 2d and e and Fig. S2d and e). Warming significantly decreased the pH of alpine meadows while increasing it in screes (Fig. 3a and Fig. S3a). Warming significantly increased SOC, STN, and P/M in screes, with nonsignificant impacts in steppe and meadow (Fig. 3c, f, and i and Fig. S3c, f, and i). Changes in microbial diversity indicated that experimental warming tended to reduce fungal diversity. However, warming decreased the bacterial diversity of steppe but significantly increased it in screes. (Fig. 4 and Fig. S4).

Warming impacts on multiple ecosystem functions

Ecosystem multifunctionality indexes differed significantly among three mountain grasslands, with the EMF, AEMF, and BEMF indexes greater in meadow than in steppe and screes (Fig. 5). The multiple ecosystem functions of mountain grasslands responded differentially to warming, with the indexes of EMF, AEMF, and BEMF generally declining in alpine steppes and meadows yet increasing in alpine screes (Fig. 5). Specifically, warming had negative, positive, and neutral impacts on the EMF indexes in steppe, meadow, and screes, respectively (Fig. 5e and f). However, warming had no significant impacts on the AEMF of all three mountain grassland ecosystems (Fig. 5a and b). We further found that warming significantly enhanced the BEMF index in screes, while significantly reducing the BEMF index in steppe and meadow (Fig. 5c and d).

Relationships of plant and soil factors with ecosystem functions

The association patterns among the EMF, AEMF, and BEMF indexes and various vegetation and soil variables were comprehensively assessed (Fig. 6a). The results indicated that EMF was primarily associated with vegetation coverage, height, AGB, *E*, SOC, POC, B-*H*, B-*Chao* and B-*E*. The AEMF index was linked to coverage, height, AGB, SOC, NH_4^+–N, STN, POC, P/M, B-*H*, B-*Chao* and B-*E*. However, the BEMF index was mainly related to coverage, height, AGB, *E*, POC, F-*H*, B-*H*, and B-*Chao*. Further analysis showed that warming caused variations in EMF index were associated with variations in vegetation coverage, height, *S*, *H*, pH, SOC, MAOC, POC, P/M, F-*E*, B-*H*, B-*Chao* and B-*E* (Fig. 6b). In addition, we found that warming-induced variations in BEMF index was mainly related to the changes in height, pH, SOC, MAOC, POC, P/M, F-*E*, B-*H*, B-*Chao* and B-*E* (Fig. 6b). Moreover, warming drove changes in the

AEMF index, which were significantly and positively linked to alterations in vegetation *S*, *D*, and *H* (Fig. 6b).

Controls of multiple ecological functions in mountain grasslands

We used the structural equation model (SEM) to infer warming impacts on the AEMF, BEMF, and EMF indexes across mountain grasslands (Fig. 7). Path analysis of the SEM demonstrated that warming mainly regulated the EMF and BEMF indexes via productivity and soil carbon, whereas its effect on the AEMF index mainly through productivity (Fig. 7a, c, and e). Regarding the total impact on ecosystem functions, we found that biodiversity was the predominant contributor to the AEMF index, whereas soil carbon was the primary contributor to the BEMF index (Fig. 7b and d). However, for the overall impact on the EMF index, the contributions of biodiversity, productivity, and soil carbon substantially exceeded those of other variables (Fig. 7c). We therefore concluded that the divergence responses of ecosystem functions to warming across mountain grasslands were highly driven by biodiversity, productivity, and soil carbon.

Discussion

Warming effects on individual ecological functions

This study revealed a clear elevational divergence in how individual functions of mountain grasslands respond to climate warming, regulated primarily by natural hydrothermal limitations and vegetation types (Li et al. 2016; Ganjurjav et al. 2018). In low-elevation steppe ecosystem, warming exacerbates drought stress by increasing evapotranspiration (Niu et al. 2008), leading to declines in plant coverage, aboveground biomass (AGB), and diversity (*S* and *H*), a response consistent with global arid ecosystems (Ganjurjav et al. 2016; Shi et al. 2024). Conversely, the high-elevation scree ecosystem exhibited positive responses to warming relief from temperature limitation. Enhanced plant height, coverage, and AGB reflected physiological release under improved growth conditions. However, in the mid-elevation meadows, warming triggered a complex response characterized by increased species richness but declined plant biomass. Warming induced significant declines in dominance and productivity of sedge and cushion plants that coincided with the expansion of grass and forbs, ultimately leading to a decline in meadow productivity (Zhang et al. 2022; Zhou et al. 2023). This shift in species composition represents a crucial mechanism driving the restructuring of alpine plant communities under future climatic conditions.

It was found that SOC and STN contents were enhanced by warming in screes, whereas no significant effects were observed in steppe or meadow (Fig. 3 and Fig. S3). Such remarkable carbon and nitrogen sequestration capacity observed in scree ecosystem could be mainly attributed to slowing organic matter decomposition and increasing plant carbon inputs. By enhancing plant coverage, height, and AGB in screes, warming increased the input of plant litter and root exudates, which in turn elevated soil

carbon and nitrogen contents (Bjorkman et al. 2018). In addition, warming also could alter soil carbon composition, potentially undermining long-term carbon sink stability (Bardgett et al. 2013). While warming enhanced the accumulation of both organic carbon and POC in scree systems, we observed a concurrent decrease in MAOC. P/M represented the stability of soil carbon, and a higher value indicated lower carbon stability. The differential responses of carbon components under warming provide new insights into understanding soil carbon stability. This phenomenon may stem from the influx of substantial labile carbon from increased aboveground biomass, preferentially forming particulate organic matter. Simultaneously, increased plant diversity along with substantial inputs of carbon sources stimulates microbial diversity, particularly bacteria (Feng et al. 2023). This structural shift in the soil carbon composition has important implications for the long-term stability of carbon sink in mountain grassland ecosystems.

The divergence in ecosystem multifunctionality under warming

The present study revealed divergent trends in how ecosystem multifunctionality responded to warming in Tibetan mountainous grasslands. Specifically, we observed decline trends in the EMF, AEMF, and BEMF indexes in the steppe, an increase in the screes, and no significant change in the meadow (Fig. 5). Such divergent changes in ecosystem multifunctionality indexes under warming could be primarily governed by vegetation types and hydrothermal constraints, which together determined the magnitude of ecosystem functioning responses to warming (Wang et al. 2023). In low-elevation steppe, water supply is the dominant limitation for plant growth and ecosystem functioning (Wang et al. 2023). Warming intensified drought stress through increased evapotranspiration, and led to significant decreases in vegetation coverage, AGB, and plant diversity, which collectively drove the decrease in EMF (Chen et al. 2016; Pennekamp et al. 2018; Leyrer et al. 2024). Conversely, in high-elevation screes, where is primarily temperature-limited, and warming served to alleviate this constraint. We observed that warming significantly enhanced plant height, coverage, and AGB in the scree, which could increase litter and root exudates inputs, thereby providing more source of labile carbon to the soil carbon pool (Mazzilli et al. 2015). The results further indicated that warming caused a shift in microbial community which were likely due to increased input of plant-derived carbon sources (Zhao et al. 2025), consequently contribute to a rise in soil carbon observed in the scree ecosystem. Thus, in the temperature-limited screes ecosystem, the positive effect of warming was amplified through both plant and microbial pathways, which could comprehensively explain the pronounced enhancement of the BEMF and EMF indexes.

Further path analysis within SEM further indicated that the effects of warming on EMF and BEMF indexes were exerted through productivity and soil carbon, while its effect on AEMF was mainly mediated by productivity (Fig. 7). The standardized total effects further showed that biodiversity was the predominant contributor to AEMF, whereas soil carbon was the primary driver for BEMF (Fig. 7). This emphasized that assessing ecosystem responses required a multidimensional approach tailored to specific functional attributes. For the overall EMF, biodiversity, productivity, and soil carbon all exerted

substantially stronger influences than other variable, underscoring their synergistic roles in maintaining overall ecosystem service provision. In conclusion, our findings demonstrated that the responses of Tibetan mountain grasslands to warming were fundamentally mediated by ecosystem types and environmental constraints through distinct mechanistic pathways. The divergent responses were primarily driven by the differential responses of biodiversity, productivity, and soil carbon dynamics. This finding highlighted that incorporating ecosystem-specific characteristics was essential for accurate climate change prediction and sustainable ecosystem management across Tibetan montane grasslands.

Uncertainties and Implications

Although this study analyzed warming impacts on the multifunctionality of Tibetan mountain grasslands, there were still several uncertainties and research limitations warrant consideration. First, the functional assessment of present study focused primarily on biodiversity, production, and carbon and nitrogen sequestration. We did not quantify other key ecological functions such as hydrological regulation, anti-interference ability, resilience, and resistance stability, which were crucial for soil and water conservation and ecosystem stability (Hu et al. 2021). Second, the relatively short duration of the experiments (three growing seasons) may not fully capture long-term ecological dynamics, such as cumulative warming effects on species composition and soil carbon and nutrients dynamics (Wei et al. 2025). Third, the mechanisms underlying functional changes including microbial network complexity and plants-fauna interactions have not been fully quantified, limiting a mechanistic understanding of the observed multifunctional responses (Wang et al. 2024). Moreover, other environmental factors such as precipitation regimes, nutrient availability, extreme climatic events, may modulate or even warming effects on ecosystem functions. Addressing these limitations is therefore critical for developing evidence-based management and climate adaptation in grasslands across high-elevation ecosystems.

Conclusion

This study revealed that warming exerted divergent effects on the multiple ecological functions of the Tibetan mountainous grasslands, with the ecosystem multifunctionality indexes (EMF, AEMF, and BEMF) generally decreased in steppe, increased in screes, and remained unchanged in meadow. The divergence responses of ecosystem multifunctionality indexes to warming across mountain grasslands were highly driven by biodiversity, productivity, and soil carbon. In addition, warming influences ecosystem multifunctionality vary between aboveground and belowground compartments, with AEMF index predominantly driven by biodiversity and productivity responses but the BEMF index strongly governed by soil carbon. These findings underscore that high-elevation grassland responses to climate warming are not uniform across ecosystem types, mediated by the differences in ecosystem types and hydrothermal constraints. These knowledges provide a valuable foundation for enhancing the comprehension and prediction of ecosystem functioning responses to future climate warming across widespread mountainous grasslands of the Tibetan Plateau and provides a scientific basis for developing proper management practice to mitigate climate change.

Declarations

Conflict of interest

The authors declare no competing financial interests.

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Author contributions

Shuaihao Bai: Data curation, Formal analysis, Investigation, Visualization, Writing - original draft. Wen Yang: Formal analysis, Methodology, Investigation. Guomin Xue: Data curation, Investigation. Yongwen Liu: Supervision, Resources. Lihua Tian: Software, Methodology. Gao-Lin Wu: Validation, Supervision. Jingxue Zhao: Conceptualization, Funding acquisition, Writing - review & editing.

Data availability

All data generated and analyzed in this study are available from the corresponding author upon reasonable request.

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Figures

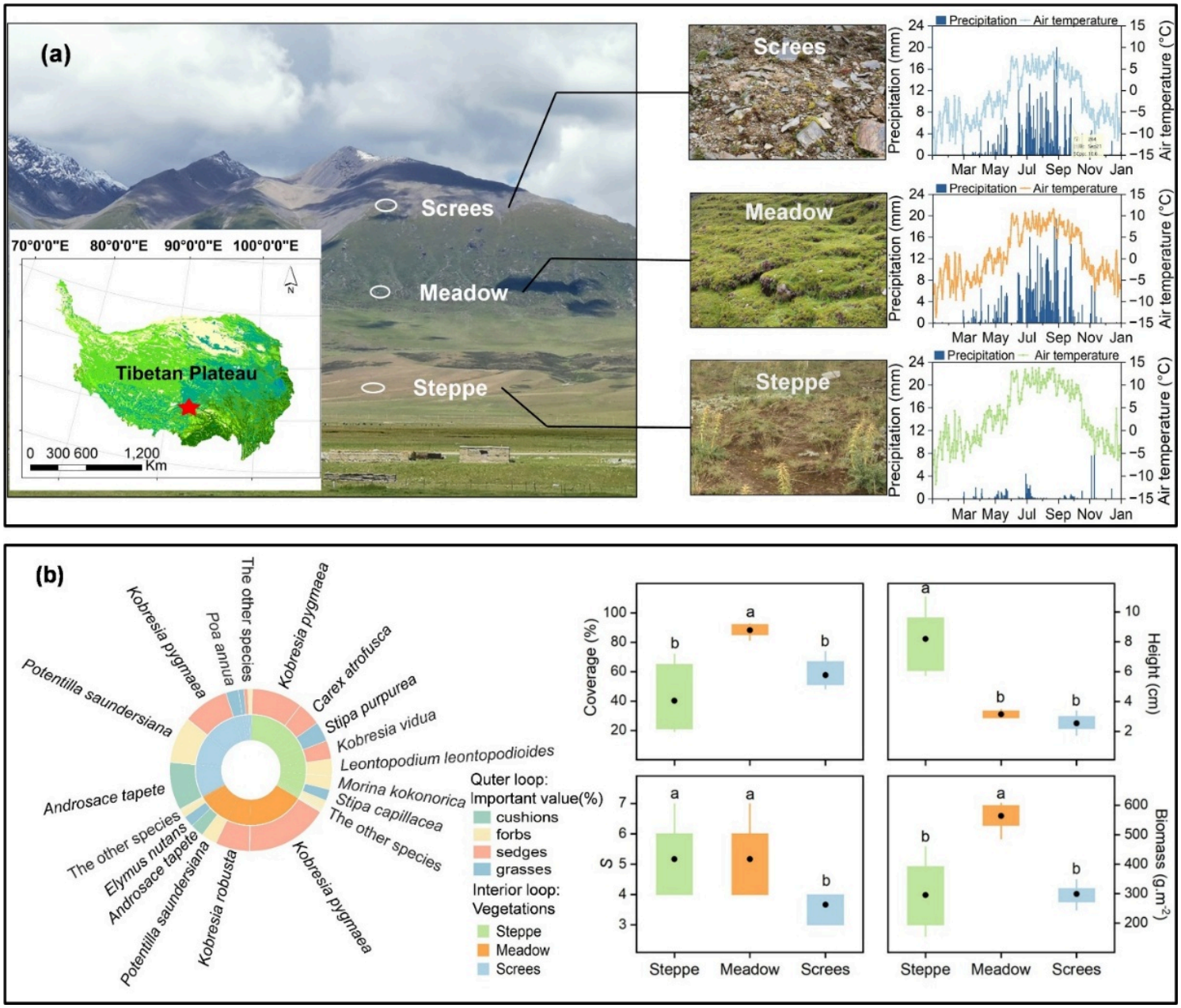


Figure 1

Location and vegetation characteristics of three vegetation types distributed along the southern slope of the Nyaiqentanglha Mountains. (a) The location, images, and environmental conditions of three vegetation types. (b) Coverage, plant height, species richness (*S*), and biomass of selected three vegetation types. Distinct letters indicate significant differences among vegetation types.

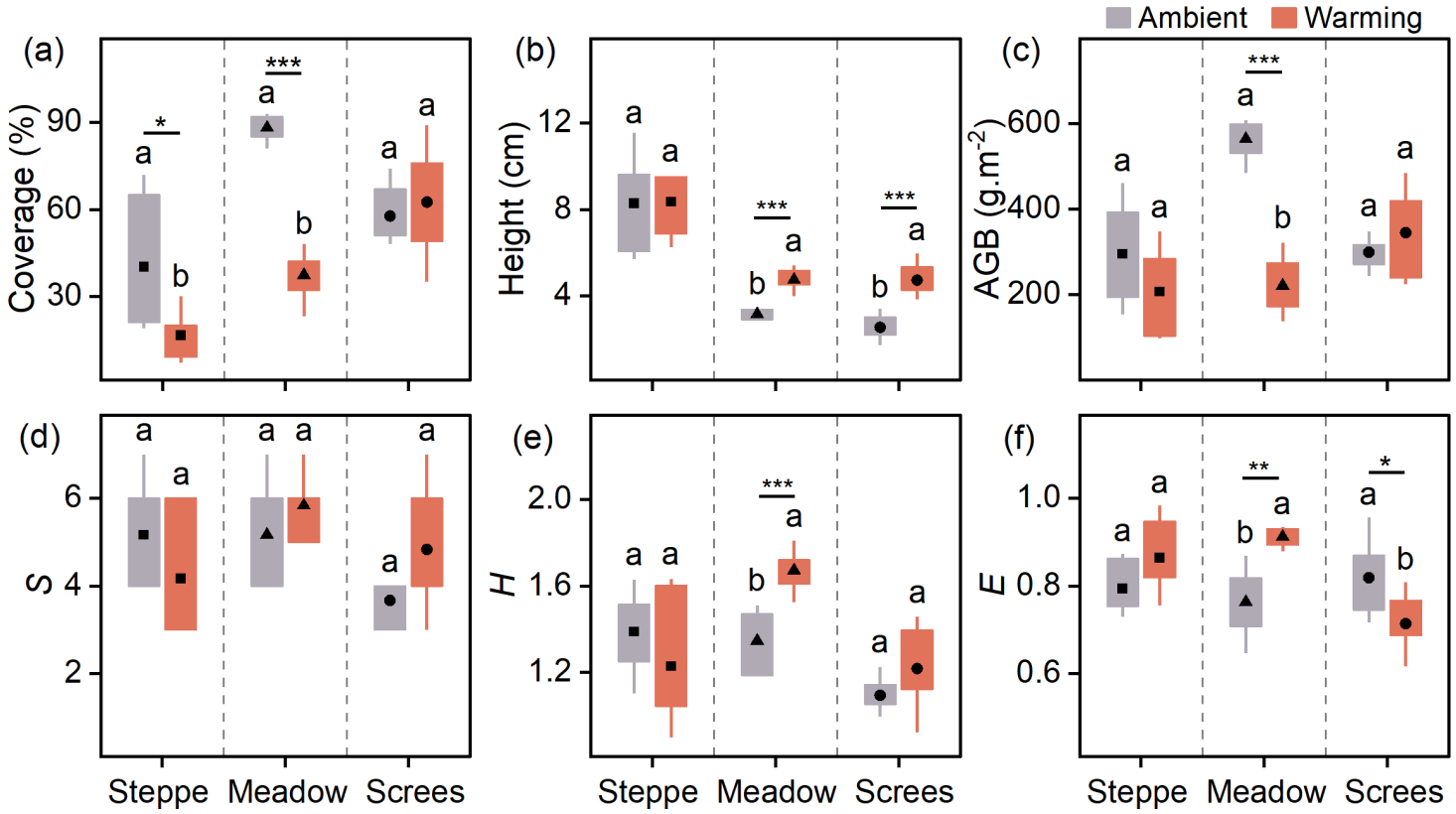


Figure 2

Changes of vegetation productivity and plant diversity across vegetation types under warming and ambient conditions. (a) Coverage, vegetation coverage; (b) Height, plants height; (c) AGB, aboveground biomass; (d) *S,* richness index; (e) *H*, Shannon Wiener index; (f) *E,* evenness index. Distinct letters indicate significant differences among vegetation types. Asterisks represent the significant differences between warming and ambient treatments. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

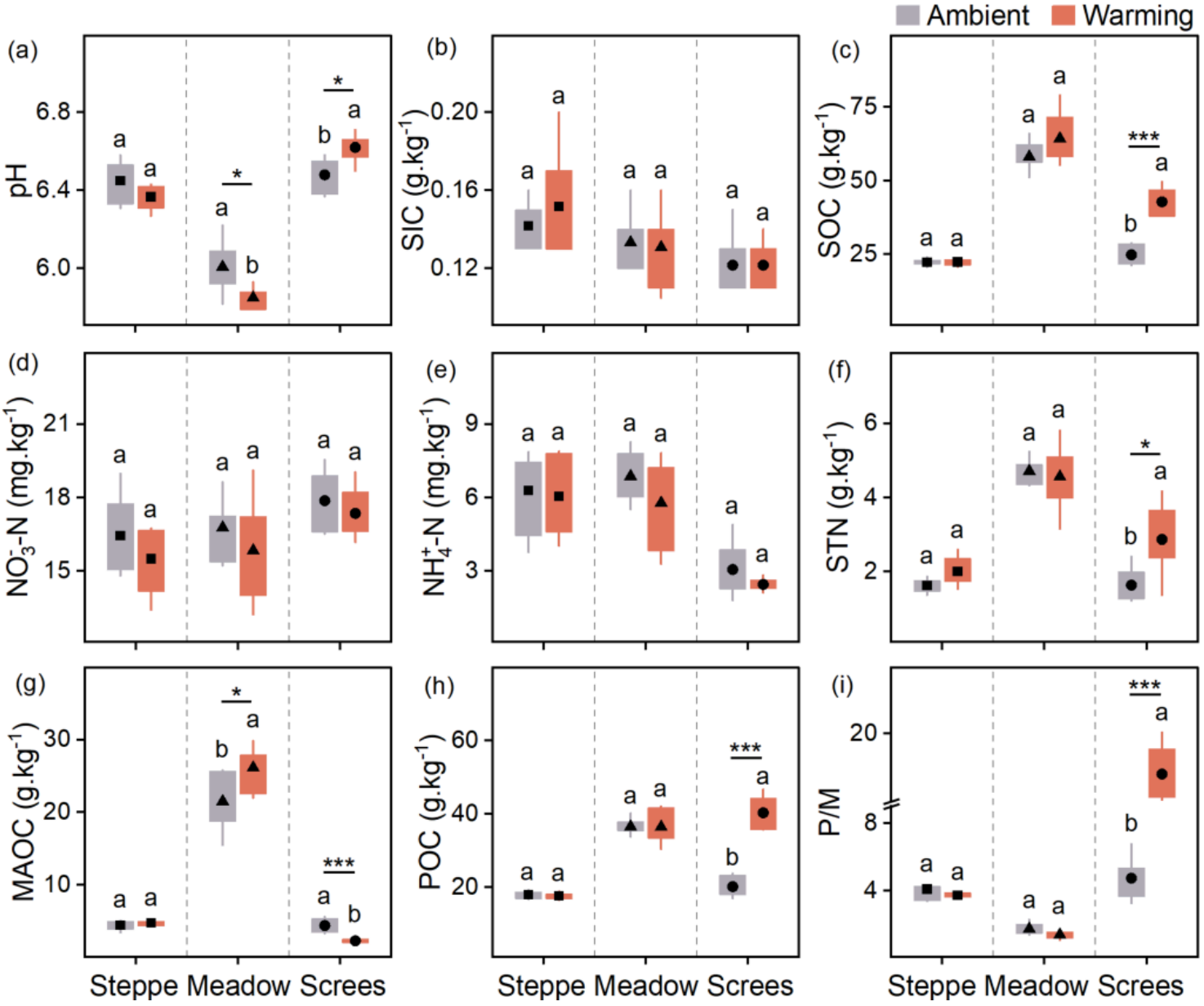


Figure 3

Changes of soil physical and chemical properties across vegetation types under warming and ambient conditions. (a) pH, soil pH; (b) SIC, soil inorganic carbon; (c) SOC, soil organic carbon; (d) NO_3^--N, nitrate nitrogen; (e) NH_4^+-N, ammonia nitrogen; (f) TN, total nitrogen; (g) MAOC, mineral - associated organic carbon; (h) POC, particulate organic carbon; (i) P/M, the ratio of POC to MAOC. Distinct letters indicate significant differences among vegetation types. Asterisks represent the significant differences between warming and ambient treatments. *, p<0.05; **, p<0.01; ***, p<0.001.

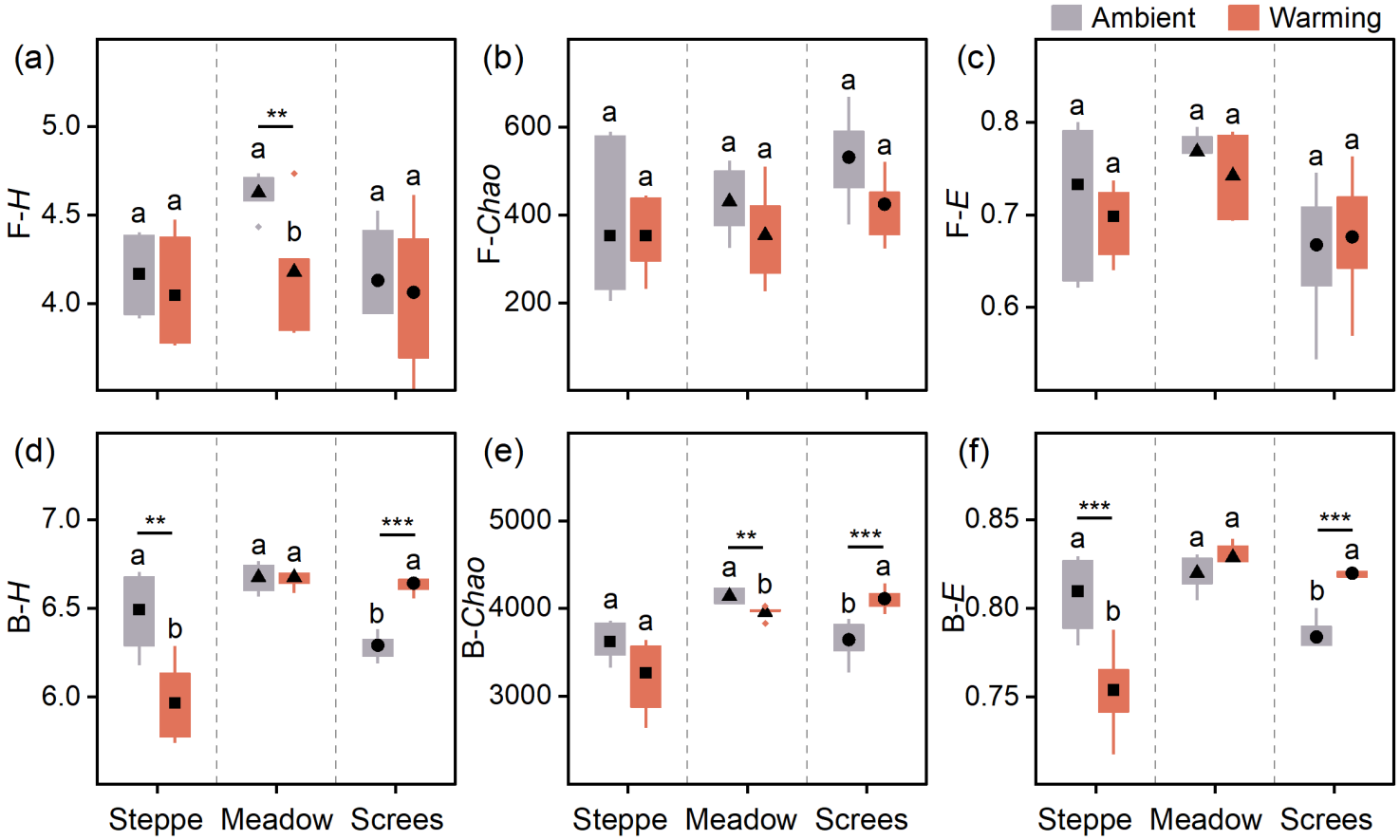


Figure 4

Changes of soil microbial diversity across vegetation types under warming and ambient conditions. (a) F-*H*, Shannon - Wiener index of fungi; (b) F-*Chao*, Chao index of fungi; (c) F-*E*, Shannon Evenness index of fungi; (d) B-*H*, Shannon - Wiener index of bacteria; (e) B-*Chao*, Chao index of bacteria; (f) B-*E*, Shannon Evenness index of bacteria. Distinct letters indicate significant differences among vegetation types. Asterisks represent the significant differences between warming and ambient treatments. *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

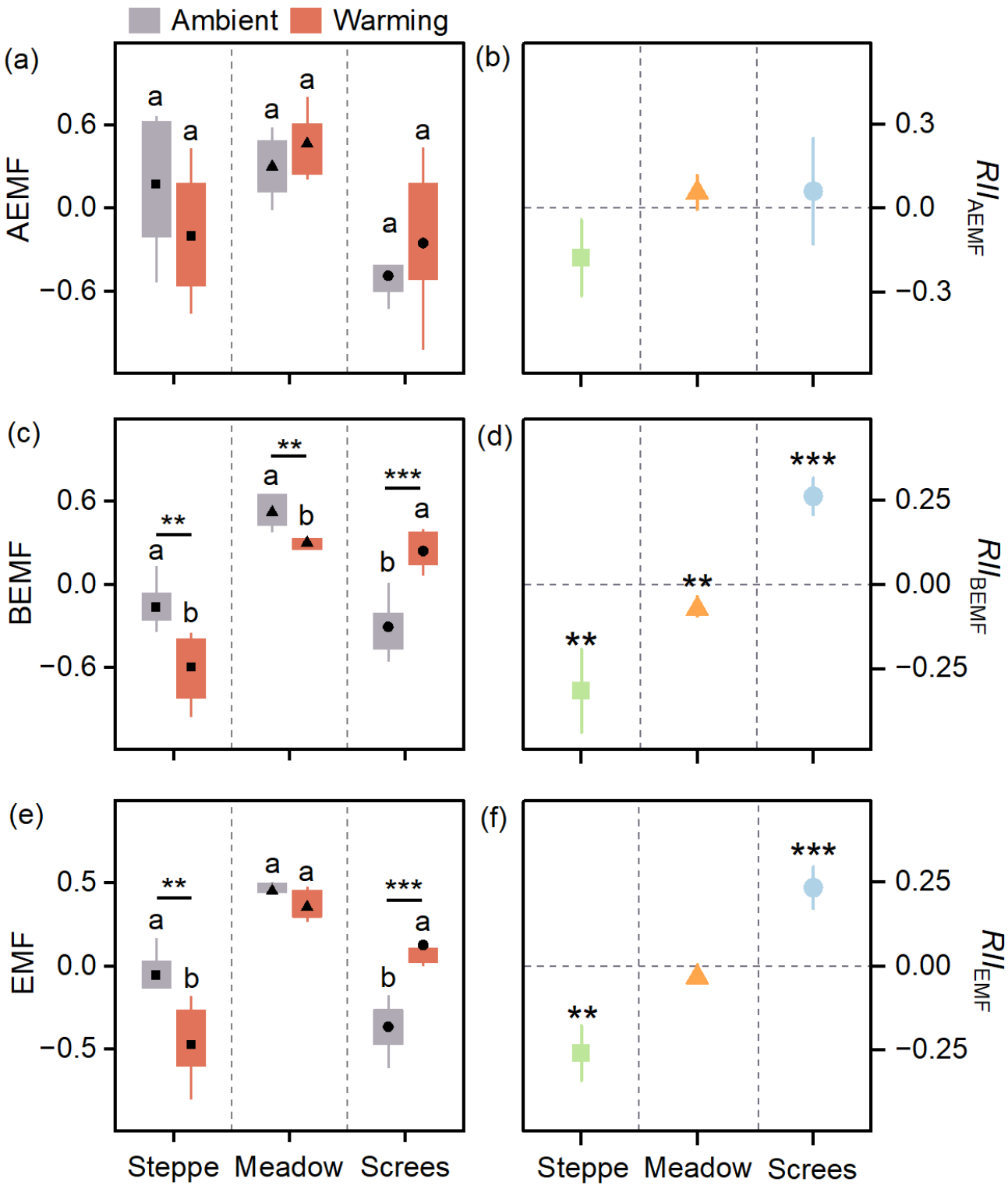


Figure 5

Changes of (a and b) aboveground ecosystem multifunctionality index (AEMF), (c and d) belowground ecosystem multifunctionality index (BEMF), and (e and f) the overall ecosystem multifunctionality index (EMF)across vegetation types under warming and ambient conditions. Distinct letters indicate significant differences among vegetation types. Asterisks represent the significant differences between warming and ambient treatments. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

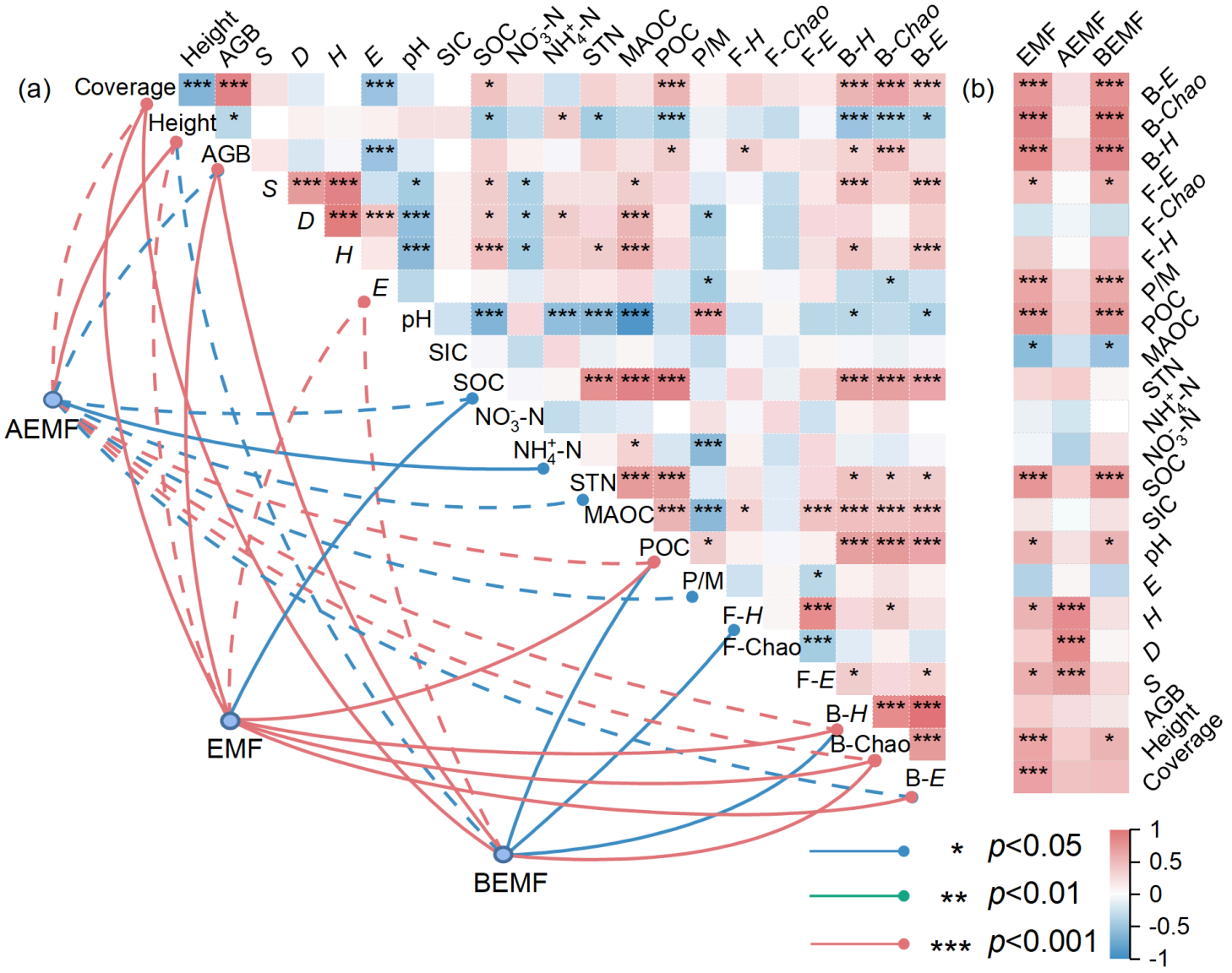


Figure 6

Correlation coefficients among ecosystem multifunctionality indexes, vegetation characteristics, and soil properties. (a) Correlations between EMF, AEMF, BEMF and vegetation characteristics, soil properties. (b) Correlations between warming-induced changes of ecosystem multifunctionality indexes (the *RII* values of EMF, AEMF, BEMF) and warming-induced changes (the *RII* values) of vegetation characteristics and soil properties.

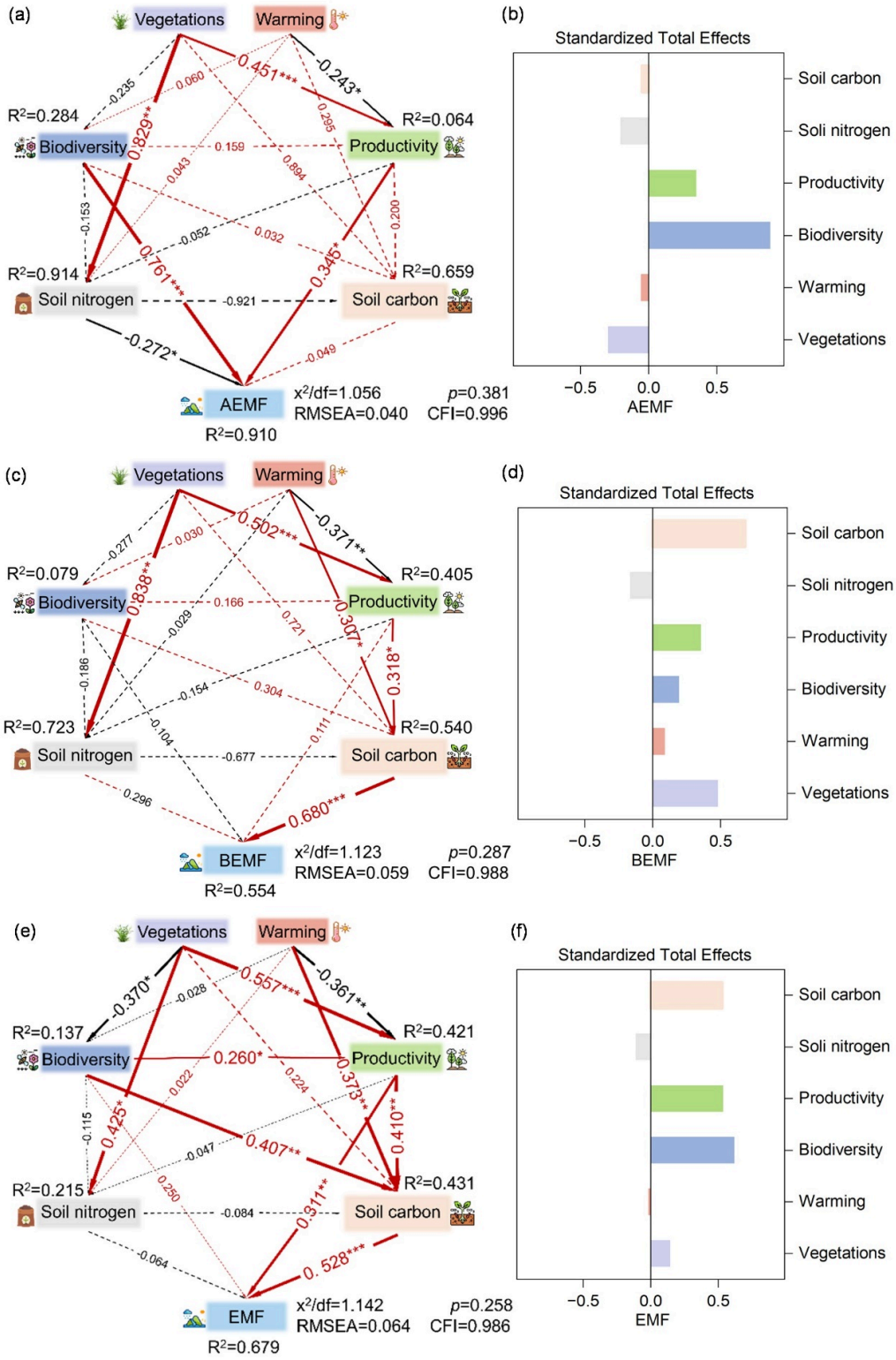


Figure 7

Structural equation models depicting the direct and indirect effects of warming and vegetations on (a and b) the aboveground ecosystem multifunctionality (AEMF), (c and d) the belowground ecosystem multifunctionality (BEMF), and (e and f) the overall ecosystem multifunctionality (EMF) via biodiversity, productivity, soil nitrogen, and soil carbon. The red and black arrows indicate positive and negative effects, respectively. Dashed arrows indicate insignificant effects. Numbers besides the arrows

represent standardized path coefficients, proportional to the arrow thickness. The proportion of variance explained (R^2) appears alongside the variables, and goodness-off statistics are shown below each model. Standardized total effects (b, d, f) derived from the structural equation models depicted, respectively. Numbers along the bars represent the standardized total effect values. *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$.

Supplementary Files

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