Warming-induced tipping points of Arctic and alpine shrub recruitment

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Shrub recruitment, a key component of vegetation dynamics beyond forests, is a highly sensitive indicator of climate and environmental change. Warming-induced tipping points in Arctic and alpine treeless ecosystems are, however, little understood. Here, we compare two long-term recruitment datasets of 2,770 shrubs from coastal East Greenland and from the Tibetan Plateau against atmospheric circulation patterns between 1871 and 2010 Common Era. Increasing rates of shrub recruitment since 1871 reached critical tipping points in the 1930s and 1960s on the Tibetan Plateau and in East Greenland, respectively. A recent decline in shrub recruitment in both datasets was likely related to warmer and drier climates, with a stronger May to July El Niño Southern Oscillation over the Tibetan Plateau and a stronger June to July Atlantic Multidecadal Oscillation over Greenland. Exceeding the thermal optimum of shrub recruitment, the recent warming trend may cause soil moisture deficit. Our findings suggest that changes in atmospheric circulation explain regional climate dynamics and associated response patterns in Arctic and alpine shrub communities, knowledge that should be considered to protect vulnerable high-elevation and high-latitude ecosystems from the cascading effects of anthropogenic warming.

Results

Shrub recruitment was highly correlated with atmospheric circulation indices (Fig. 1F). Specifically, shrub recruitment in Greenland was strongly related to variability of the AO and AMO. AO from June to July was significantly and positively related with recruitment from 1871 to 1970, whereas during recent decades (1962 to 2010), the AMO from June to July showed a significant negative correlation with recruitment ($r = 0.395$ in 1871 to 1970; $r = -0.934$ in 1962 to 2010; $P < 0.001$ in both cases and considering detrended series). June to July AMO drove the regional mean temperature of those months, with warmer conditions being associated with a higher AMO index (Fig. 24 and Dataset S1). However, decreased precipitation was also associated with high AMO values. Consequently, temperature and precipitation had negative and positive effects on shrub recruitment, respectively. May to July Niño 4 had negative associations with shrub recruitment on the Tibetan Plateau (Fig. 1F) ($r = -0.806$ in 1871 to 1940, $P < 0.05$; $r = -0.73$ in 1941 to 2010, $P = 0.06$ for detrended series). Increased mean temperature in May to November and lower June to October precipitation were also related to Niño 4 since the 1930s (Fig. 24 and Dataset S1).

In addition, recruitment was significantly and negatively correlated with decadal mean May to November temperature in 1941 to 2010. A positive correlation was found between recruitment and monsoon season precipitation.

Moving correlation analyses showed that the sign of the temperature sensitivity of recruitment shifted from positive to negative after passing recruitment tipping points in both locations (Fig. 2B).

Discussion

There is growing concern that Arctic and alpine ecosystems may reach tipping points under accelerating climate change (10–12). Our study now adds strong evidence that climate-induced tipping points during the past decades have already reversed the formerly increasing trend in shrub recruitment across these cold biomes. Moreover, our results importantly provide a long-term context for the quantification of shrub recruitment variations in relation to changes in climatic circulation patterns.

Author contributions: X.L. and E.L. designed research; X.L. and U.B. collected data; X.L., F.B., and J.J.C. analyzed data; and X.L., E.L., F.B., J.J.C., and U.B. wrote the paper. The authors declare no competing interest.

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Results

Recruitment of high Arctic shrub species peaked in about 1961 to 1970 in coastal east Greenland near Ittoqqortoormit (Fig. 1A–E), whereas the recruitment peak of alpine juniper shrub occurred three decades earlier on the Tibetan Plateau (1931 to 1940). Shrub recruitment declined subsequently in both study regions (Fig. 1E and SI Appendix).

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The observed variability in shrub recruitment and the underlying relationships with changes in atmospheric circulation patterns indicate complex responses of spatial and temporal shrub regeneration and expansion in the Arctic and the Tibetan Plateau. For example, shrub recruitment peaked in different time periods (Fig. 1E), suggesting a high degree of heterogeneity of...
shrub encroachment in these distant treeless areas. We hypothesize that the accelerated greening trends prior to peak recruitment were associated with climate warming in both arctic and alpine regions (13).

The declines of shrub recruitment likely resulted from drought stress associated with changes in large-scale atmospheric circulation patterns. In Greenland and on the Tibetan Plateau, high AMO and Niño 4 were associated with a warmer and drier climate (Fig. 2 and Dataset S1), leading to unfavorable recruitment conditions with low soil moisture. Despite the long-standing notion that warming has accelerated greening across those cold regions, some studies have demonstrated that tundra vegetation exhibited strong, locally contingent responses to climate (14). In particular, shrub recruitment is strongly limited by the available soil moisture (14). Future warming may thus further impair shrub recruitment or increase mortality rates by intensifying soil drying. Similar to our results, shrub growth at more than one-third of the Pan-Arctic sites has already indicated warming-induced drought stress, showing an early warning signal of a state shift in shrub communities (15).

This study highlights the tight links between large-scale atmospheric circulations and shrub recruitment in the Arctic and on the Tibetan Plateau. Atmospheric circulation patterns could thus be used to forecast spatiotemporal shifts in shrub recruitment, and thereby assist in projecting future vegetation shifts in cold biomes. Our data also indicated that the optimal climate for shrub recruitment has already been passed in two remote and ecologically important cold regions.

Materials and Methods

Shrub recruitment series were established from two datasets, including 2,770 individuals in Ittoqqortoormiit and on the Tibetan Plateau (8, 9). The climate data mainly used were obtained from the Climate Explorer (http://climexp.knmi.nl) and National Oceanic and Atmospheric Administration websites (https://psl.noaa.gov/gcos_wgsp/Timeseries/). Linear regressions and moving Pearson correlation analyses were applied to assess the relationships between shrub recruitment series and climate. See SI Appendix for further details.

Data Availability. All shrub recruitment data used for analyses are available in Dataset S1. All other study data are included in the main text and supporting information.

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