GEOSCIENCES

Special Topic: The Tibetan Plateau

Complex vegetation responses to climate change on the Tibetan Plateau: a paleoecological perspective

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Rapid major shifts in vegetation types are most often attributed to abrupt climate changes. However, recent studies have revealed non-linear vegetation responses to current global warming on the Tibetan Plateau [1]. This also seems to be the case for the Holocene vegetation on the Tibetan Plateau. This high-elevation region is under the control of the Asian monsoon, causing relatively moist summers and dry winters. Monsoon influence rapidly decreases from the southeastern to the northwestern parts of the plateau, leading to steep climate gradients. As a consequence, the vegetation covers range from forest (with precipitation of >ca. 400 mm), steppe/meadow (precipitation ranging from ca. 200 to 500 mm) and desert (with precipitation of <ca. 200 mm) across the gradients (Fig. 1A).

From the last deglacial time to the Holocene, monsoon precipitation gradually increased in response to the summer insolation changes and to the global boundary conditions [2], reaching maximum intensity around ca. 9–6 kyr BP. Vegetation changes on the Tibetan Plateau inferred from dozens of pollen records are marked by the establishment of interglacial type ('establishment shift'), the optimum state around the mid-Holocene, and followed by the deterioration ('collapse shift') during the late part of the Holocene. Such overall trends are obviously consistent with the orbital-induced gradual monsoon changes.

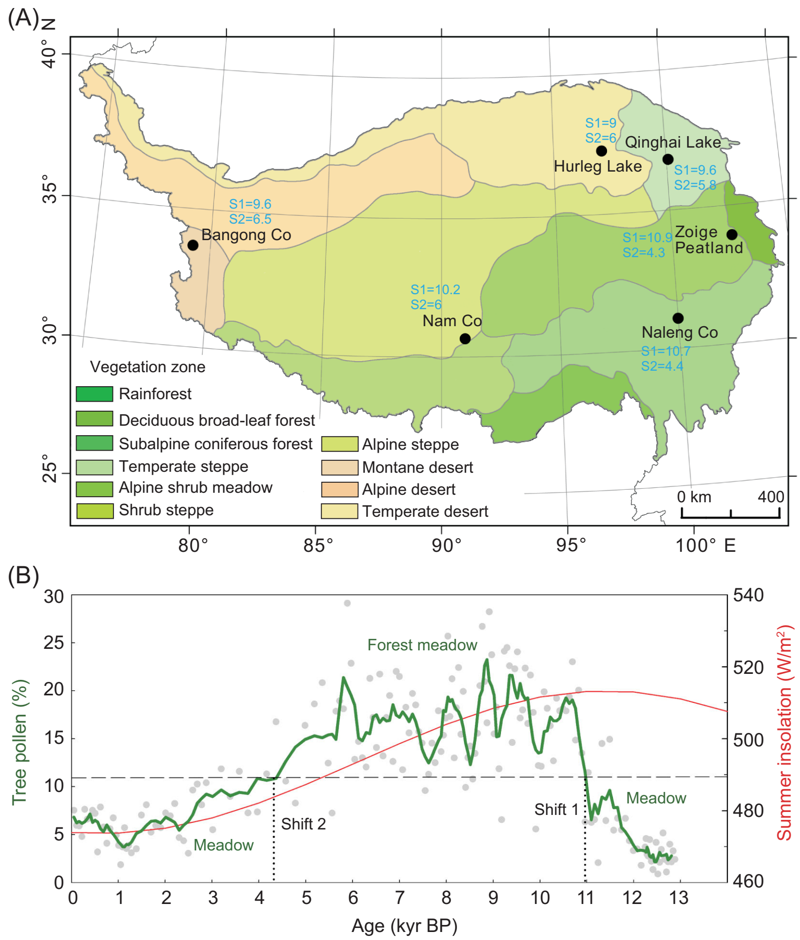

Figure 1. Modern vegetation regions and Holocene vegetation shifts on the Tibetan Plateau. (**A**) Vegetation regions, location of six representative pollen records and the timings of two vegetation shifts. These vegetation types are simplified based on Hou *et al.* (2001) [14]. (**B**) The numbers indicate the age (kyr BP) of the vegetation shifts (S1 = Shift 1, S2 = Shift 2). Tree pollen percentage (with 5-point moving mean value) from the Zoige peatland (Zhao, unpublished data) showing two vegetation type shifts at ca. 10.9 and 4.3 kyr BP, suggesting non-linear response to summer insolation at 40° N [15].

However, the Holocene vegetation changes on the plateau displayed several prominent features that are not readily explainable by such orbital-scale gradual climate trends. A first prominent feature is that both shifts are relatively abrupt (Fig. 1B). Another feature is that the timing of the onset of the vegetation shift is asynchronous for individual sites across the Tibetan Plateau. For examples, the pollen record from Naleng Lake in the south part of the Tibetan Plateau shows an abrupt vegetation change from alpine meadow to montane forest at 10.7 kyr BP and back to meadow at 4.4 kyr BP [3]. Far north to Naleng Lake, three pollen records from the Zoige Basin indicate an abrupt change from meadow to forest meadow at ca. 10.5 kyr BP and a return to meadow at 4.3 kyr BP [4]. These two sites both have the mean annual precipitation of ca. 650 mm. While at Qinghai Lake north to the Zoige Basin, which has less precipitation (300 mm), vegetation changed from steppe to forest steppe at 9.6 kyr BP and returned to steppe at 5.8 kyr BP [5]. At Nam Co (with the precipitation of 280 mm) in central Tibetan Plateau, the two vegetation shifts (between desert steppe, steppe and meadow) happened at 10.2 and 6 kyr BP [6]. In the drier Qaidam Basin, Hurleg Lake experienced two vegetation shifts occurring at 9 kyr BP (from desert to steppe desert) and 6 kyr BP (back to desert). At Bangong Co with precipitation of 50 mm, Holocene vegetation show two shifts as at Hurleg Lake around 9.6 and 6.5 kyr BP [7]. These asynchronous timings of abrupt vegetation shifts are also shown in many other Holocene pollen records from the Tibetan Plateau.

The relative abruptness and these spatially varying timings of vegetation changes are not readily explainable by the orbital-induced gradual monsoon changes, suggesting that the climate–vegetation relationships are non-linear. Given that climate trends should be synchronous under the same climate regime (e.g. the monsoon zone), these phenomena are likely caused by the existence of the threshold effect in the vegetation response to climate changes. Scheffer *et al.* [8] showed that modern ecosystems, in most cases, might be quite inert over certain ranges of conditions, responding more strongly when conditions approach a certain critical level. Such threshold effects have only been scarcely documented in the past vegetation changes. In the Sahel-Sahara dry ecosystems [9], a catastrophic vegetation shift from Savanna to desert-like conditions occurred about 5 kyr ago due to the slow gradual insolation reduction and subsequent non-linear vegetation–atmosphere feedbacks [10], or a strong low-frequency climate variability accompanied by a gradual precipitation decline [11].

The Holocene vegetation shift on the Tibetan Plateau is seemingly well explained by similar threshold effects. During the transition from the deglacial time to the Holocene interglacial, gradually increased monsoon precipitation led to the recovery of vegetation. Forest, steppe and desert could be rather stable systems across a wide range of mean precipitation levels. Therefore, establishment of new vegetation type suggests threshold precipitation levels. Relatively moist regions firstly gained this threshold leading to earlier establishment of vegetation shift, as they are closer to the threshold moisture. In contrast, climatically drier regions received this threshold precipitation much latter, causing a delayed vegetation shift. Because of the same effect, the monsoon precipitation decrease in the late Holocene could lead to a collapse in the vegetation covers, earlier for drier regions and latter for moister regions.

Determining the threshold precipitation of these vegetation shifts is a crucial issue as it is useful for evaluating the impacts of future climate changes. However, these values are only approximates as the effects of temperature and evaporations need to be discriminated. Meanwhile, internal and external feedbacks could stabilize the system and affect the threshold. Moreover, high-elevation vegetation is particularly sensitive to CO_2 changes due to lowered CO_2 partial pressure, as suggested by Herzschuh *et al.* [12] that explained the increase of meadow elements in the later Holocene in the steppe/meadow margin regions. In addition, the effects of precipitation and temperature on vegetation are also unstable under different scenarios of the CO_2 concentrations [13]. Further understanding would need much effort, in particular, through data-model comparisons.

We could also expect that this threshold effect is also applicable to ecosystems elsewhere. Given that the dominant climate factor controlling vegetation changes are spatially variable, the threshold effect would also be applicable to climate parameters other than precipitation, such as temperature, evaporation and seasonality etc. These insights suggest that our current understanding on the climate–vegetation relationship is far to be well. More new efforts would be critical for evaluating the future climate impacts and for managing the ecosystems on the Tibetan Plateau.

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