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Cite this article: Zhou HK, Yao BQ, Xu WX, Ye X, Fu JJ, Jin YX, Zhao XQ. 2014 Field evidence for earlier leaf-out dates in alpine grassland on the eastern Tibetan Plateau from 1990 to 2006. *Biol. Lett.* **10**: 20140291. http://dx.doi.org/10.1098/rsbl.2014.0291

Received: 7 April 2014
Accepted: 16 July 2014

**Subject Areas:**
ecology, environmental science

**Keywords:**
leaf-out date, alpine meadow, alpine steppe, climate change, plant phenology, Tibetan Plateau

**Authors for correspondence:**
B. Q. Yao
e-mail: bqyao@nwipb.cas.cn
X. Q. Zhao
e-mail: xqzhao@nwipb.cas.cn

Electronic supplementary material is available at http://dx.doi.org/10.1098/rsbl.2014.0291 or via http://rsbl.royalsocietypublishing.org.

Royal Society Publishing

Global change biology

# Field evidence for earlier leaf-out dates in alpine grassland on the eastern Tibetan Plateau from 1990 to 2006

H. K. Zhou[1,2], B. Q. Yao[1,2], W. X. Xu[3], X. Ye[4], J. J. Fu[1], Y. X. Jin[1] and X. Q. Zhao[5]

[1]The Northwest Institute of Plateau Biology, The Chinese Academy of Sciences, Xining 810008, People's Republic of China
[2]Key Laboratory of Adaptation and Evolution of Plateau Biota, The Chinese Academy of Sciences, Xining 810008, People's Republic of China
[3]Qinghai Institute of Meteorological Science, The Chinese Academy of Sciences, Xining 810001, People's Republic of China
[4]Research Centre for Eco-environmental Sciences, The Chinese Academy of Sciences, Beijing 100085, People's Republic of China
[5]Chengdu Institute of Biology, The Chinese Academy of Sciences, Chengdu, 610041, People's Republic of China

Worldwide, many plant species are experiencing an earlier onset of spring phenophases due to climate warming. Rapid recent temperature increases on the Tibetan Plateau (TP) have triggered changes in the spring phenology of the local vegetation. However, remote sensing studies of the land surface phenology have reached conflicting interpretations about green-up patterns observed on the TP since the mid-1990s. We investigated this issue using field phenological observations from 1990 to 2006, for 11 dominant plants on the TP at the levels of species, families (Gramineae—grasses and Cyperaceae—sedges) and vegetation communities (alpine meadow and alpine steppe). We found a significant trend of earlier leaf-out dates for one species (*Koeleria cristata*). The leaf-out dates of both Gramineae and Cyperaceae had advanced (the latter significantly, starting an average of 9 days later per year than the former), but the correlation between them was significant. The leaf-out dates of both vegetation communities also advanced, but the pattern was only significant in the alpine meadow. This study provides the first field evidence of advancement in spring leaf phenology on the TP and suggests that the phenology of the alpine steppe can differ from that of the alpine meadow. These findings will be useful for understanding ecosystem responses to climate change and for grassland management on the TP.

## 1. Introduction

Plant phenology may be one of the traits in nature that responds most to climate fluctuations [1]. There is now ample evidence that the onset of spring is advancing for plants at middle and high latitudes worldwide, in parallel with climate warming. These patterns have been documented with field observations and remote sensing, two independent methods used commonly to determine phenology [2–5].

The Tibetan Plateau (TP) is the world's largest and highest plateau and is known as its 'third pole'; temperatures there have risen rapidly in recent decades, compared with extra-tropical lower elevations [6]. The high sensitivity of its plants to climate change has attracted increasing levels of research attention [7–11]. Using remotely sensed satellite data, Yu *et al.* [7] suggested that the onset of the growing season in alpine habitats on the TP has been delayed since the mid-1990s, due to warming in winter and spring. By contrast, Zhang *et al.* [12] argued that the quality of 2001–2006 remote sensing data (based on GIMMS and NDVI) was poor; instead, they merged various sources of satellite data and detected an advanced start of the growing season over this period.

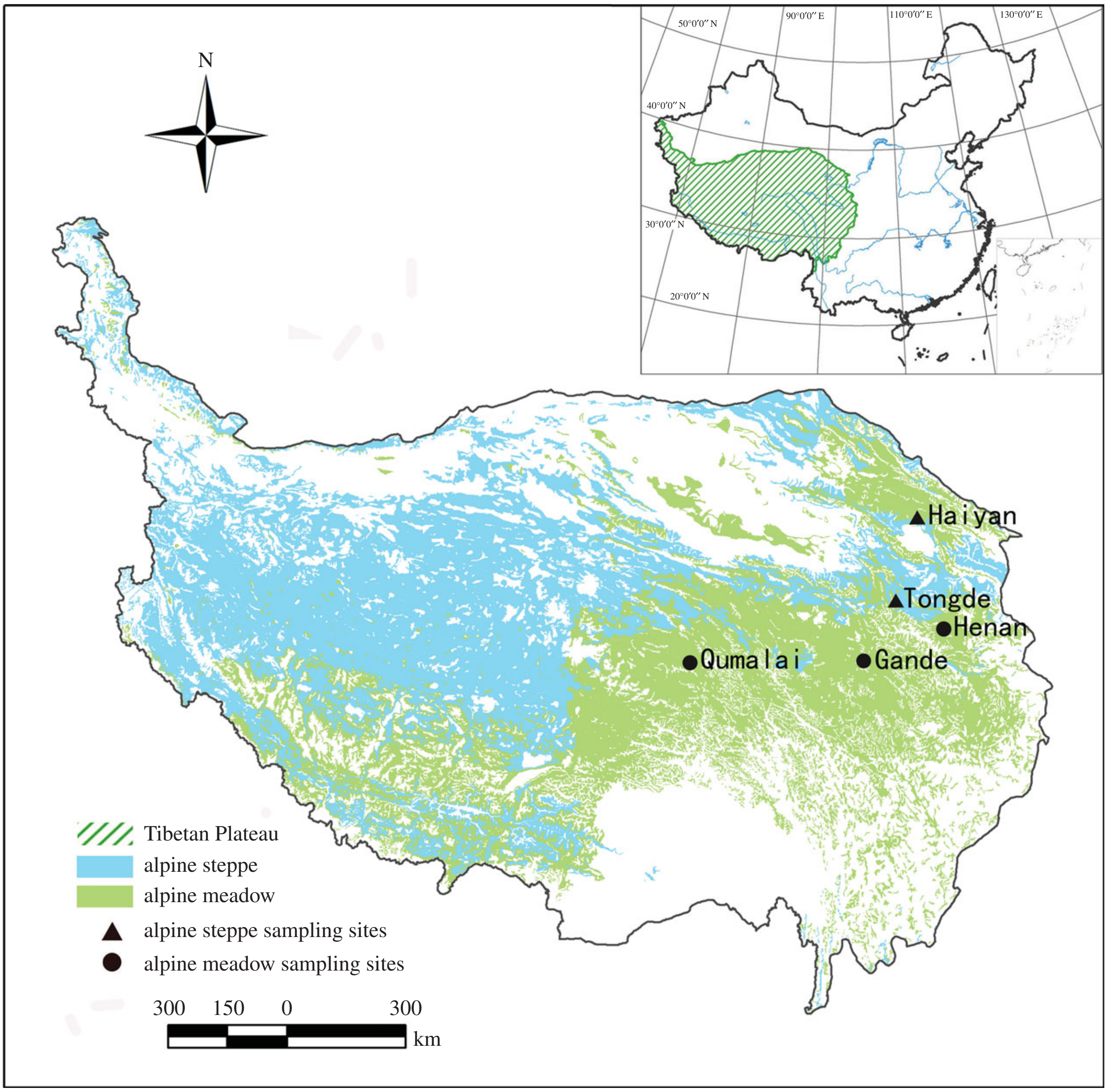


**Figure 1.** Field sampling sites on the eastern TP of central Asia. (The type and area of alpine grassland were extracted from the Vegetation Atlas of China (1 : 1 000 000) [24].) (Online version in colour.)

These conflicting results have caused debates about the issue [13–20], but direct phenological information from observations on the ground is lacking for the region, especially long-term data, due to barriers for field research posed by the harsh environment.

Using remote sensing technology to detect land surface phenology is distinctly different than identifying organism-specific phenological events using field observations [21–23]. Direct observations on the ground measure the timing of life cycle events of individual plants at the species level, while satellite monitoring estimates seasonality of large-scale, composite factors such as greenness and vegetation cover. Furthermore, traditional ground observation of phenology is based on developmental changes in plants, such as budburst and leaf-outs that differ from the land surface phenology quantified by remotely sensed spectral vegetation indices. Therefore, field evidence is urgently needed to assess phenological shifts on the cold plateau, where plants are widely recognized to be sensitive to climate change.

Here, we present field observations of 11 grassland species at five sites in two alpine vegetation communities of the eastern TP over the period 1990–2006, and we evaluate the trends in leaf-out dates at the levels of species, family and vegetation communities.

## 2. Material and methods

### (a) Study sites and plant species

Sampling was conducted at five meteorological stations across the central and eastern TP (latitude 96° to 105°E, longitude 30° to 40°N; figure 1). The major vegetation types of the region are alpine steppe and alpine meadow (figure 1). Sites were chosen to enclose grassland with relatively flat relief, in areas larger than $10 \times 10$ km. The plant species observed belong to two families: Gramineae and Cyperaceae (table 1). This species list includes almost all locally dominant plants. We chose four species at each site for observation from 1990 to 2006 in the three sites of the alpine meadow, 1990 to 1998 in Tongde site and 1997–2006 in Haiyan site (electronic supplementary material).

### (b) Data collection

Leaf-out dates were determined in repeated years, following criteria of the China Meteorological Administration [25]. Leaf-out

**Table 1.** The average leaf-out date (in Julian Days) of the 11 observed plant species and the Mann–Kendall trend test.

| species | year | | | | | | | | | | | | | | | | | $\tau$ | *p*-value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | | |
| Gramineae | | | | | | | | | | | | | | | | | | | |
| *Elymus nutans* | 110 | 117 | 123 | 114 | 119 | 123 | 117 | 112 | 112 | 115 | 119 | 118 | 115 | 116 | 115 | 117 | 117 | 0.015 | 0.967 |
| *Poa crymophila* | 108 | 130 | 134 | 113 | 128 | 125 | 121 | 113 | 106 | 112 | 118 | 120 | 111 | 128 | 121 | 102 | 111 | −0.284 | 0.126 |
| *Stipa krylovii* | 110 | 109 | 133 | 101 | 131 | 123 | 115 | 106 | 103 | 99 | 105 | 102 | 97 | 109 | 105 | 103 | 107 | −0.349 | 0.057 |
| *Aneurolepidium dasystac* | 111 | 109 | 134 | 102 | 115 | 122 | 113 | 107 | 108 | — | — | — | — | — | — | — | — | −0.167 | 0.602 |
| *Festuca ovina* | 117 | 128 | 119 | 118 | 118 | 119 | 116 | 120 | 116 | 111 | 124 | 118 | 121 | 126 | 122 | 109 | 111 | −0.075 | 0.709 |
| *Puccinellia tenuiflora* | 118 | 113 | 123 | 126 | 124 | 132 | 127 | 122 | 122 | 117 | 122 | 124 | 117 | 124 | 118 | 124 | 120 | −0.038 | 0.868 |
| *Koeleria cristata* | 119 | 119 | 115 | 119 | 117 | 115 | 114 | 109 | 109 | 111 | 115 | 115 | 115 | 103 | 109 | 105 | 112 | −0.564 | 0.003 |
| Cyperaceae | | | | | | | | | | | | | | | | | | | |
| *Kobresia pygmaea* | 131 | 139 | 127 | 137 | 142 | 152 | 135 | 134 | 130 | 128 | 139 | 128 | 128 | 144 | 129 | 119 | 127 | −0.332 | 0.082 |
| *Scirpus distigmaticus* | 118 | 120 | 126 | 128 | 124 | 121 | 127 | 122 | 124 | 116 | 122 | 124 | 119 | 117 | 118 | 120 | 118 | −0.303 | 0.105 |
| *Carex moorcroftii* | 141 | 142 | 149 | 125 | 137 | 127 | 129 | 136 | 120 | 116 | 133 | 130 | 116 | 144 | 134 | 130 | 122 | −0.267 | 0.148 |
| *Kobresia humilis* | 112 | 110 | 112 | 113 | 113 | 115 | 112 | 110 | 107 | 109 | 118 | 116 | 111 | 111 | 113 | 110 | 114 | 0.046 | 0.835 |

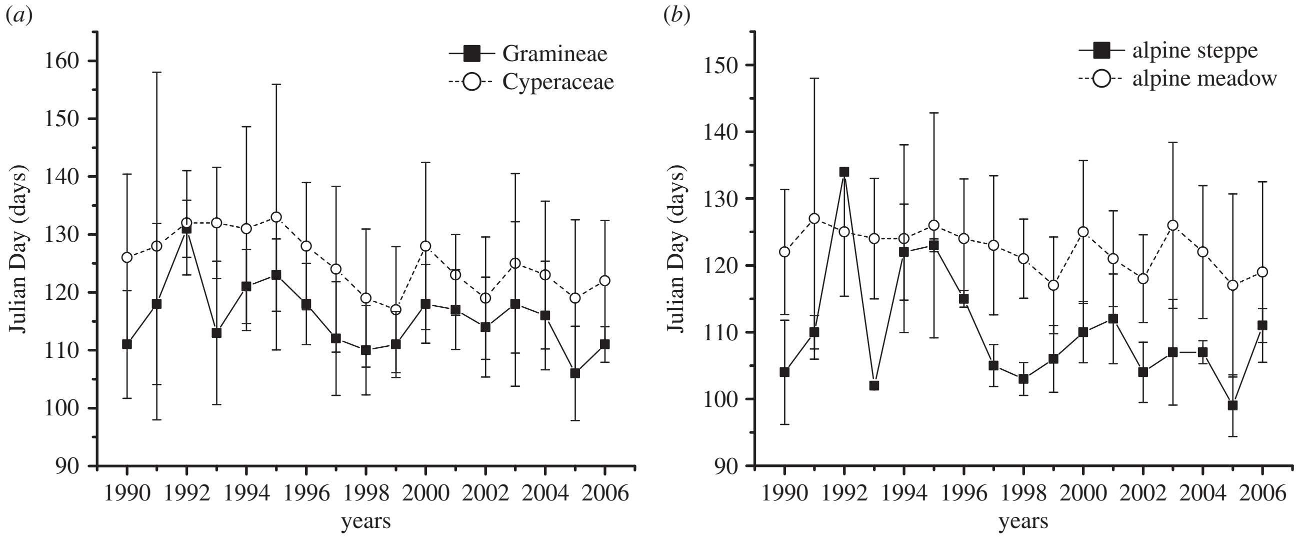


**Figure 2.** Inter-annual variations in the mean values of leaf-out date (in Julian Day) from 1990 to 2006 at the levels of (*a*) families: the Mann–Kendall tests for Gramineae ($\tau = -0.321$, $p = 0.088$) and for Cyperaceae ($\tau = -0.382$, $p = 0.041$); and (*b*) grassland vegetation communities: the Mann–Kendall tests for alpine meadow ($\tau = -0.370$, $p = 0.047$) and for steppe ($\tau = -0.141$, $p = 0.457$). Error bars show 1 s.d.

was determined as the date when 50% of the directly observed grassy area had turned green and had a height of approximately 1 cm. Observations at each site were conducted every 2 days.

### (c) Statistical analyses

The yearly average leaf-out dates were analysed with the Mann–Kendall trend test using software R at the levels of species, families and vegetation communities. For the families and the vegetation communities, we calculated the means across species within each of their respective categories.

## 3. Results

At the species level, green-up dates of nine species appeared to have advanced from 1990 to 2006, but this pattern was only significant for one species (*K. cristata*; table 1). At the family level, green-up dates of both grasses ($p = 0.088$) and sedges ($p = 0.041$) had advanced, and the dates for the two groups were significantly correlated (Spearman correlation, $R = 0.797$, $p$-value $< 0.001$) (figure 2*a*). On average, grasses were delayed by about 9 days per year, compared with sedges. At the level of the grassland community type, meadow leaf-out dates advanced significantly ($p = 0.047$) and dates on the steppe were also earlier though not significant (figure 2*b*). The leaf-out dates for the two vegetation communities were not correlated (Spearman correlation, $R = 0.467$, $p = 0.059$).

## 4. Discussion

In this paper, we used field observations to assess the trends in leaf-out dates at the levels of species, family and vegetation community and found that the advanced trend was the main pattern in the TP, as shown in table 1 and figure 2. Contrary to a previous publication by Yu *et al.* [7], we did not find significant delays in leaf-out dates in the mid-1990s.

The observed species share the same life form, and possibly the same cues for the onset of spring phenology [26]. This might be why we found a larger degree of advancement in green-up dates as compared with others [4,26–28], although most of the trends were not significant (table 1). Perhaps the relatively short observational span was not enough to tease apart the impact of the relatively large inter-annual variation in phenology (mean s.d. = 8.89 days, more than 10 days for 4 spp.) that is affected by the large-scale climatic variability [1], though our study duration was relatively longer.

Overall, we found that grasses and sedges have a similar pattern of advancement (based on trends and correlation patterns) and, in addition, grasses generally leafed out later than sedges (mean difference 9 days; figure 2). This similarity in the phenological plasticity in response to environmental change has important implications for community stability—the patterns of coexistence of the two dominant plant families on the TP seem to be maintained [29], although their phenologies have advanced.

Moreover, results indicate that the overall phenology advanced in the alpine meadow, consistent with remote sensing results in the eastern TP [8,11,13]. We hypothesize that the lack of significance in the trend of the alpine steppe was probably due to the fact that these sites were typically assessed at lower elevations (3110 and 3160 m for Haiyan and Tongde, respectively) than the alpine meadow sites (altitudes, 3600–4300 m). Interestingly, the spring phenology at lower elevations was previously found to be less sensitive to climate change [8]. These extremely different phenological responses of the two major vegetation communities will result in more contiguous leaf-out dates.

We note that our sampling sites were in the eastern TP, where alpine steppes are relatively uncommon (figure 1). The inclusion of data from the western TP, where the steppe spreads across a large area, would help to elucidate the observed patterns. Regardless, the clear advancement in leaf-out dates that we detected on the meadows, and in sedge, is highly relevant for any future grassland management of the TP and for understanding the influence of global climate changes on plants growing at high elevations.

Acknowledgements. We thank Dr Q Li for his help in data analysis and the several reviewers that have substantially improved the clarity of our manuscript.

Funding statement. This work was supported by the National Natural Science Foundation of China grants to M.S. (nos. 31201836, 31172247, 41030105) and by a 'Strategic Priority Research Program' grant from the Chinese Academy of Sciences (no. XD A05070202).

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