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Altered precipitation patterns and simulated nitrogen deposition effects on phenology of common plant species in a Tibetan Plateau alpine meadow

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ABSTRACT

The interactive effects of five seasonal precipitation distribution patterns and two levels of N deposition (ambient and doubled) on phenological traits of six common plant species were studied in an alpine meadow of the Tibetan Plateau for two consecutive years. Seasonal precipitation patterns included ambient (control), reduced fall/winter/spring – increased summer, increased fall/winter – reduced spring, increased fall/winter – reduced spring/summer, and increased spring – reduced summer. Our results indicate that: 1) phenological trait variation was predominantly due to species differences ($P < 0.0001$), yet flowering dates for annual forbs and perennial graminoids were more synchronous under wetter conditions in the second season, which likely led to more intense competition for soil resources between these two groups; 2) the effect of treatments on species phenological traits appeared in the second growing season only, suggesting that phenological shifts in these species lag behind abiotic conditions and/or require cumulative exposure to these factors (≥2 years); 3) redistributing dormant season and spring precipitation to summer caused earlier flowering and longer flowering duration for perennial graminoids (*P. pratensis*, *K. setchwanensis*, respectively) and earlier and shorter duration of fruiting for the annual forb *G. paludosa*; yet N addition diminished and/or reversed these effects. Moreover, augmenting fall and winter precipitation at the expense of spring and summer precipitation decreased all phenological traits of *P. anserina* except for flowering date, but N addition reversed these effects, and; 4) interannual variation in species phenology was strongly influenced by environmental differences among the two growing seasons rather than different precipitation patterns and N addition. We discuss how seasonal shifts in precipitation and/or greater N deposition in the future may impact plant species fitness, species coexistence, and vegetation composition in alpine meadow ecosystems of the Tibetan Plateau.

1. Introduction

Seasonal and single-event precipitation intensity has shifted significantly during the 21th century due to the changes in atmospheric circulation and hydrological processes associated with global climate change over most land areas (Solomon et al., 2007). Precipitation pattern is one of the most important and complex factors of climatic change in many regions because it influences both the timing and length of growing seasons (IPCC, 2007), as well as the availability of soil moisture and nutrients to resident plant species (Weltzin et al., 2003). However, the manner in which shifting precipitation impacts plant phenology will vary for different ecosystems. For example, precipitation timing was found to trigger green-up and influence the duration of growth and reproductive phenology of most plant species in dry deserts (Fox, 1990; Abd El-Ghani, 1997; Ghazanfar, 1997), fruiting phenology of dominant shrubs (*Erica multiflora* and *Globularia alypum*) in the mesic mediterranean of central Spain (Peñuelas et al., 2004), as well as dominant grasses in mesic North American grasslands (Fay et al., 2000). Furthermore, altered precipitation appears to affect the tim-

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ing of phenological events in a species-specific manner (Shen et al., 2011; Dorji et al., 2013; Mazer et al., 2013).

Anthropogenic nitrogen (N) deposition is also an important factor of global change, which has increased notably at the global scale since the industrial revolution (Matson et al., 2002). Moreover, N deposition is predicted to increase over the next few decades accompanying the release of nitrogenous waste gas in industry and the application of fertilizers in agriculture (Galloway et al., 2004). Increased N deposition alters resource accumulation, allocation patterns and the duration of plant growth (Bowman et al., 2006; Cleland et al., 2006; Smith et al., 2012), as well as species biodiversity within plant communities for a broad range of ecosystems (Emmett et al., 1998; Stevens et al., 2004; Madan et al., 2007; Bobbink et al., 2010; Pardo, 2010). For example, the flowering dates of two forb species were extended when exposed to N addition alone, but when exposed to increased winter precipitation (snowpack) and N addition simultaneously, flowering dates were unchanged in an alpine tundra (Smith et al., 2012). Such studies suggest that increased N deposition can shift phenology of plant species depending on how it interacts with precipitation (i.e., synergistic or antagonistic) (Cleland et al., 2007; Gordo and Sanz, 2010).

Although shifting plant phenology over the last several decades has been detected for species within manipulative field experiments (Peñuelas et al., 2004) and at the community level for natural ecosystems via long-term satellite monitoring (Bradley et al., 2011), the factors causing these shifts and how they influence phenological traits of species is often illusive. While the general trend of earlier spring onset and lengthened growing season has been observed for the northern hemisphere under experimental warming (Porter et al., 2013), a shortened growing season at the plant community level was attributed to winter and spring warming during the last two decades in the Tibetan Plateau of eastern China (Yu et al., 2010; Luedeling et al., 2011). The patterns observed in the Tibetan Plateau have also been attributed to grassland degradation, thawing-freezing processes, and their combined effects with climate warming (Chen et al., 2011). Furthermore, others speculate that later spring onset of phenology in the Tibetan Plateau, as measured by reduced normalized difference vegetation index (NVDI) values, may be attributed to increasing levels of atmosphere pollution, rather than changes in a specific climate variable (Yi and Zhou, 2011). Although green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011 (Zhang et al., 2013) and the roles of warming and precipitation are known to be important factors (Che et al., 2014), the influence of interacting factors on plant species phenology in the Tibetan Plateau remains unclear.

The Tibetan Plateau is a vast elevated region in central Asia that covers 2,500,000 km^2 and is considered the main driver and amplifier of local and global climate change (Liu and Chen, 2000; Dong et al., 2012). Previous studies on global change over the eastern Tibetan Plateau in China have reported increases in total annual precipitation during the latter half of the twentieth century (Liu and Chen, 2000; Niu et al., 2004; Zhang et al., 2004; Qin et al., 2006; Yu et al., 2012) and substantial increases in bulk N deposition between 1980s and 2000s (Liu et al., 2013). Furthermore, combined evidence from observed trends and global climate models predict that winter average precipitation will increase over the Tibetan Plateau (IPCC, 2007), yet it is still difficult to accurately predict anticipated changes in seasonal precipitation distribution in specific, small-scale regions due to variable vegetation cover types, complex topographic features, and distorted albedo feedbacks associated with extensive snow cover (e.g., Ye and Gao, 1979; Tang et al., 1979; Domrös and Peng, 1988). For example, precipitation has decreased in the humid zone of the eastern and southeastern Tibetan Plateau (Yang et al., 2011); however, spring, summer, and winter precipitation has generally increased within alpine meadows in this region (Xie et al., 2010). Yet, in spite of documented changes in precipitation and N deposition in alpine meadow plant communities in the southeastern subregion, and previous studies to ascertain how annual or seasonal precipitation affects plant phenology (Che et al., 2014), it remains unclear how the combined factors of seasonal precipitation and concurrent anthropogenic increases in N deposition are impacting phenological traits critical to the persistence of common plant species (Liu and Yin, 2001).

Because phenological variation among plant species plays a key role in species coexistence (Rathcke and Lacey, 1985; Cleland et al., 2007), growth dynamics of plant communities, trophic-level interactions (Post and Forchhammer, 2008; Post et al., 2008; Fabina et al., 2010), and regulates carbon sequestration and energy exchange by vegetation (Yu et al., 2012), we designed a study to clarify the roles of seasonal precipitation patterns and increased N deposition on shifting plant phenology in an alpine meadow plant community in the southeastern region of the Tibetan Plateau. Ambient N deposition was increased two-fold with fertilizer application and precipitation was captured and then redistributed to simulate four potential scenarios, including 1) reduced fall-winter-spring and increased summer, 2) increased fall-winter and reduced spring, 3) increased fall-winter and reduced spring-summer, and 4) increased spring and reduced summer. During two successive growing seasons, we tracked phenological traits (i.e., dates of flowering and fruiting, as well as durations of growing, flowering and fruiting) for six common herbaceous species. We asked three questions:

1) Which phenological traits are most variable among the six common plant species?
2) Does precipitation redistribution and N deposition interact to shift phenological traits of species?
3) Which microenvironmental factors are most correlated with phenological traits of plant species in alpine meadow of the Tibetan Plateau?

2. Materials and methods

2.1. Study site

This study was conducted at Chinese Academy of Sciences, Zoige Station for High Grassland and Wetland Studies. The station is located on the eastern Tibetan Plateau at 3570 m a.s.l., 400 km north of Chengdu, Sichuan Province, China (32°26′9.79″N, 102°21′59.28″E). A 1-ha area at the station was fenced and livestock grazing was excluded in 2007. The field plot where the experiment was performed is less than 500 m^2, and its slope is approximately 0.6° and 1.6 °C, respectively (from meteorological station in Hongyuan County, unpublished data). Melting of the winter snowpack is usually complete by late April or early May, and depends on climate differences each year. The region is characterized as typical continental plateau climate with high solar radiation, a short, cool summer (mean maximum/minimum temperature in July: 14.6/7.6 °C) and a long, cold winter (mean maximum/minimum temperature in January: −3.0/−17.2 °C). The growing season is influenced by a southeastern wet monsoon period; most of the total annual precipitation (77.2%, i.e., approximately 606.8 mm) occurs between early May and the end of September. While aboveground biomass reaches its peak production potential in August, plant growth often ends and herbaceous species senesce in late September or early October due to diminished precipitation and the arrival of cold air from Siberia.

The soil is Mat Crygelic Cambisols (Chinese Soil Taxonomy Research Group, 1995) in line with Gelic Cambisol, which consists of 19% clay, 66% silt and 15% sand, with a pH = 5.3 ± 0.4 (0 cm to 10 cm, soil-water ratio of 1:2.5). The vegetation is typical alpine meadow that is used for yak and sheep grazing. The plant community is