Flowering and Fruiting Phenology of 24 Plant Species on the North Slope of Mt. Qomolangma (Mt. Everest)

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Abstract: Phenological background information for alpine species is limited from extremely high altitudes. Flowering and fruiting phenology was monitored for 24 plant species at 5,180 m a.s.l. near the base camp area on the north slope of Mt. Qomolangma (Mt. Everest) in Tibet, western China. The dates of first flowering, peak flowering, end of flowering, first fruiting, peak fruiting and flowering period were recorded. There was a wide variation in onset of flowering, long flowering duration, a relative synchrony between the onset of flowering and fruiting, and one species was exclusively vegetative. These results suggest that the species have evolved various phenological strategies as adaptations to the short growing season with limited resources and pollinators in this harsh alpine environment at extremely high elevations. With a background of global warming, local plant species will represent an advancing trend in onset of flowering.

Keywords: Alpine; Global warming; Phenology; Qinghai-Tibet plateau

Introduction

It is widely recognized that the phenology of plants may be modified by the environment (Lieth 1975) and this effect is intensified at higher elevations because of seasonal variation of temperature (Hansen et al. 1981; Smith et al. 1999). If the predicted global warming of 1.1-6.4 °C occurs before the end of this century, alpine vegetation will be one of the world's most endangered vegetation types (IPCC 2007). Knowledge of patterns of flowering and fruiting in alpine environments provides an important baseline against which responses to future global warming can be measured. Nevertheless, background information is rather scarce for some specific high altitude geographic zones such as the Qinghai-Tibet plateau which, at over 4,000 m in average elevation (Liu et al. 2000), is the highest and biggest plateau in the world (Zheng 1996). At the southwestern edge of this plateau plants can be found growing at 5,180 m near the base camp of the north slope of Mt. Qomolangma (Mt. Everest).

Because of its high elevation, the Qinghai-Tibet plateau is experiencing the effects of climate change earlier and faster than the global average (Liu and Chen 2000). A warming-drying trend has been detected on the plateau, including the Mt. Qomolangma region, over the last 40 years (Ren et al. 2004) and there is every expectation that this trend will continue. Under the influence of changing climate, the phenology of high alpine plant species will most likely respond quite significantly. Due to the relatively harsh environmental conditions, and problems of

accessibility, few detailed and long-term phenological studies have been carried out in high alpine areas, especially in the Mt. Qomolangma region. Consequently, little knowledge and few records are available about flowering and fruiting patterns among local representative plants, as well as their relations to environmental variables under a global warming background. This study of an alpine plant community near the base camp of Mt. Qomolangma provides much needed baseline phenological data for a high alpine environment.

To survive in these stringent ecological conditions, alpine plant species are likely to evolve characteristics related to the timing of flowering and fruiting, but direct empirical tests are limited, especially in alpine environment with extremely high elevation. Therefore, it is hypothesized that the constraints imposed by extreme alpine environments will select for relative synchrony in phenological patterns among local plant species. To test this, a study was designed to record the timing of flowering and fruiting of 24 plant species in the base camp area of Mt. Qomolangma during the growing season in 2005. The major focus was on flowering and fruiting patterns of local representative plant species, and also on potential change in onset of flowering under a global warming background.

1 Methods

1.1 Study site

The study was conducted in the base camp area on the north slope of Mt. Qomolangma, Tibet, western China (86°48'51" E, 28°15'2" N, elevation 5,180 m; Figure 1) during the snow-free period from April to August, 2005. The ground consists of gravels and sands with an average slope of about 50 degrees. Most plant species grow together in small clusters, or as individuals growing on small cushion plants. The prevailing winds are strong and from the north, with occasional southern winds during this study period.

Temperature and precipitation data from 1971 to 2004 were obtained from the nearest meteorological station, at Dingri county (87°6'6" E, 28°30'42" N, elevation 4,300 m) which is approximately 100 kilometers north of the study site. Average monthly air temperatures range from -7.04 °C in January and 12.02 °C in July, with the 34-y average annual temperature of 2.95 °C. Average monthly air temperatures are below 0 °C from November until early April, rise quite quickly to peak in mid-July and drop quickly from late September. The 34-y average annual precipitation is 296.4 mm, with a low in March (0.6 mm) and peak in August (120.8 mm). Mean monthly precipitation is less than 1.0 mm from November until late March, increases dramatically to peak in mid-August and drops quickly after that (Figure 2). Yang et al. (2006) demonstrated that mean annual temperature increased by 1.03 °C in our research area between 1971 and 2004, but there was no significant change in precipitation. However, the temperature increases generally occurred during the winter months and did not coincide with the growing season.

As a major scenic spot and an important base for climbers and tourists, the base camp area receives some disturbance from adjacent areas which are grazed by yaks, the major means of local transportation. It was not possible to carry out repeated observations on individual plants because they were unpredictably destroyed by yak grazing. Therefore phenological events were monitored at the whole species level. After a preliminary survey of the area, an area was chosen that had a relatively rich plant community and in which most species were accessible for repeated and convenient observation and recording. Within this area, 24 plant species in 14 families were selected for phenological study (Table 1). Another 10 species, such as *Dracocephalum* sp., *Rheum* sp., *Saxifraga* sp. and *Urtica* sp., etc. in 7 families, were relatively common locally, but were excluded from the surveys because of their excessively scattered distributions. The most abundant species in the community were *Oxytropis falcata*, *Draba handelii* and *Potentilla parvifolia* and the least were *Pedicularis* oederi and *Saussurea* sp. which were represented by only a few individuals. Nomenclature of plant species throughout the text follows Flora Xizangica (Wu 1983-1987).

1.2 Phenological observation

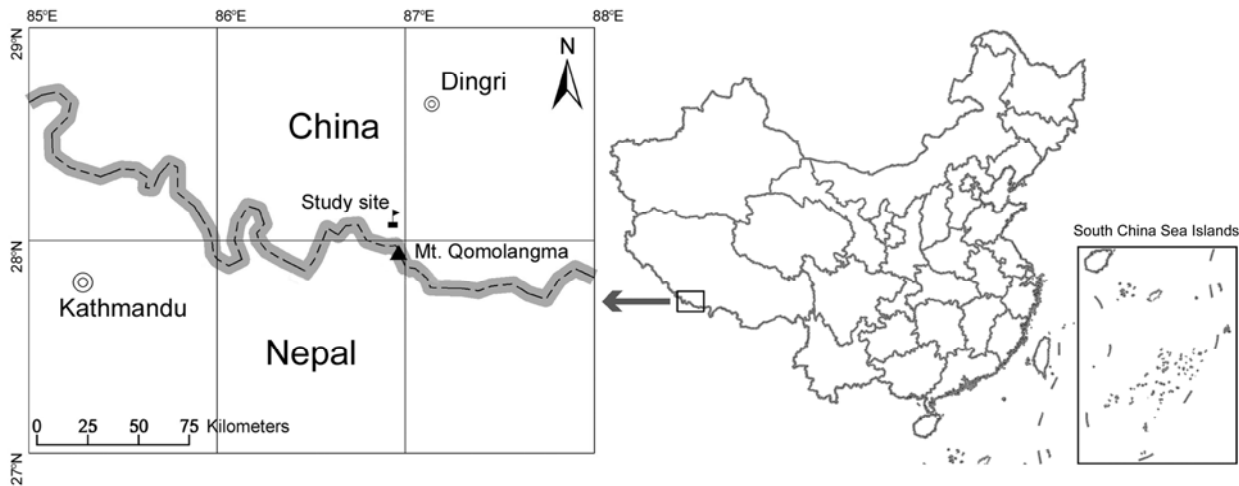Flowering and fruiting phenology was recorded for 24 study species daily from early May

Figure 1 Location of the study site near the base camp of Mt. Qomolangma at the southwestern edge of the Qinghai-Tibet plateau at 5,180 m in the Rongbu valley, western China
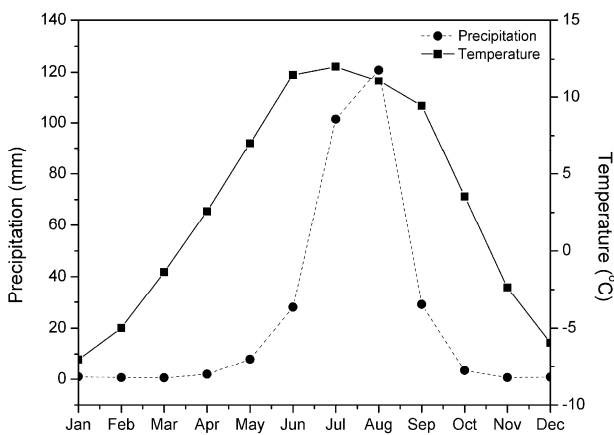

Figure 2 Monthly means (1971-2004) of temperature and precipitation at Dingri Station, about 100 km north of the study site

to late August, 2005. Because individual plants within a species live in such a wide range of conditions at this site and some flowers and fruits often appear in hidden locations, it was difficult to precisely define phenological dates. Moreover, some species had hundreds of small individuals (e.g. *Androsace umbellata* and *Arenaria pulvinata*) and it was impractical to monitor them all. Primack (1980) included only those days on which plants were 'flowering strongly', which was interpreted as having > 50% of their flowers were open. Primack's protocol was followed for dates of peak flowering and fruiting; peak fruiting was the date on which 50% of flowers developed to fruits. Although 50% is an arbitrarily chosen value, it

better represents a time when flowering and fruiting reached peak in the population as a whole. In addition, the dates of first and last flowering, and first fruiting were recorded. Duration of flowering was calculated as the difference between first and last days of flowering for each species. Logistical difficulties of prolonged high altitude and health made it impossible to monitor dates of final fruiting and observations were terminated in late August. Moreover, some extreme weather conditions, such as heavy snow on 11 July 2005, and unpredictable grazing also disturbed regular observation. To test for relationship between onsets of flowering and fruiting, first dates of flowering and fruiting were converted to calendar days (day 1 was January 1st, 2005; Table 1), and were then analyzed by linear regression using SPSS 13.0. It was not possible to determine either the first dates of flowering or fruiting for 11 species and these were excluded from the analysis.

2 Results

Flowering and fruiting patterns for the 24 plant species varied widely, yet there were distinct patterns (Figure 3). The dates of first flowering and first fruiting of the remaining 13 species were strongly and positively correlated ($R^2 = 0.878$, p <0.01; Figure 4). *Ephedra sinica* was the only species that did not flower or produce fruit during this growing season.

Table 1 Flowering and fruiting patterns of 24 plant species in the base camp area of Mt. Qomolangma, Tibet, western China. All are herbaceous species, except *Potentilla parvifolia*, which is a shrub. "+" means actual phenophases occurred later than observed or actual flowering duration was longer than observed. "-" means actual phenophases occurred earlier than observed. Data in parentheses represent calendar days of dates of first flowering and fruiting.

Species	Family	Flowering date				Fruiting date	
		First	Peak	Last	Duration (days)	First	Peak
Anaphalis tibetica Kitam.	Asteraceae	- 30 Jun	4 Jul	23 Aug +	54+	23 Jul	11 Aug
Androsace umbellata Merr.	Primulaceae	11 May (131)	23 May	11 Jul	61	4 Jul (185)	1 Aug
Arenaria pulvinata Edgew.	Caryophyllaceae	22 Jun (173)	14 Jul	23 Aug +	62+	17 Jul (198)	21 Aug
Astragalus monticolus P. C. Li et Ni	Leguminosae	- 30 Jun	- 30 Jun	23 Aug +	54+	14 Aug	17 Aug
Astragalus sp.	Leguminosae	1 Jul (182)	16 Jul	15 Aug	43	4 Aug (216)	18 Aug
Corydalis boweri Hemsl.	Papaveraceae	16 Jul (197)	1 Aug	23 Aug +	38+	11 Aug (223)	19 Aug
Delphinium albocoeruleum Maxim.	Ranunculaceae	27 Jul (208)	6 Aug	23 Aug +	27+	14 Aug (226)	23 Aug +
Draba handelii O. E. Schulz	Brassicaceae	18 May (138)	23 May	19 Aug	93	1 Jul (182)	29 Jul
Draba oreades Schrenk	Brassicaceae	- 30 Jun	5 Jul	22 Aug	51+	5 Jul	11 Aug
Draba sp.	Brassicaceae	- 30 Jun	5 Jul	20 Aug	51+	5 Jul	11 Aug
Ephedra sinica Stapf	Ephedraceae	-	-	-	-	-	-
Heracleum sp.	Apiaceae	2 Aug (214)	12 Aug	23 Aug +	21+	21 Aug (233)	23 Aug +
Leontopodium dedekensii (Bur. et Franch.) Beauv.	Asteraceae	4 Jul (185)	11 Jul	23 Aug +	50+	7 Aug (219)	23 Aug +
Microula sikkimensis Hemsl.	Boraginaceae	15 Jul (196)	20 Jul	11 Aug	27	2 Aug (214)	14 Aug
Oxytropis falcata Bunge	Leguminosae	28 May (148)	23 Jul	23 Aug +	87+	23 Jul (204)	13 Aug
Oxytropis glacialis Benth. ex Bunge	Leguminosae	5 Jul (186)	31 Jul	18 Aug	44	5 Aug (217)	17 Aug
Pedicularis oederi var. *sinensis* (Maxim.) Hurus.	Scrophulariaceae	14 Jul (195)	27 Jul	23 Aug+	40+	12 Aug (224)	23 Aug +
Potentilla parvifolia Fisch.	Rosaceae	8 Jun	14 Jul	23 Aug+	76+	-	-
Rhodiola rosea L.	Crassulaceae	- 30 Jun	2 Jul	13 Aug	44+	14 Jul	23 Aug +
Saussurea gnaphalodes (Royle) Sch. Bip.	Asteraceae	21 Jul	19 Aug	23 Aug +	33+	-	-
Saussurea graminea Dunn	Asteraceae	26 Jul (207)	11 Aug	23 Aug +	28+	10 Aug (222)	22 Aug
Saussurea sp.	Asteraceae	15 Aug	17 Aug	23 Aug +	8+	-	-
Sedum fischeri Raym.-Hamet	Crassulaceae	- 30 Jun	- 30 Jun	26 Jul	26+	12 Jul	27 Jul
Thalictrum cultratum Wall.	Ranunculaceae	- 30 Jun	16 Jul	10 Aug	41+	29 Jul	23 Aug +

The date of first flowering of the remaining 23 species ranged from mid-May to mid-August; 3 began flowering in May, 9 each in June and July, and 2 in August. The first species to begin flowering was *Androsace umbellata* on 11 May and the last was *Saussurea* sp. on 15 August, a range of 96 days. Twenty one of the species came into peak flowering in July or August. The range of flowering peaks was 88 days, from 23 May for both *Androsace umbellata* and *Draba handelii*, to 19 August for *Saussurea gnaphalodes*. Seven species finished flowering before the final surveys on 23 August, and 14 species were still flowering at that time. *Androsace umbellata* was the first (11 July) to finish flowering and *Sedum fischeri* followed (26 July). Because many species were still flowering at the end of the survey period, flowering duration can only be approximated for some of the species which, for 22 species, ranged from 27 days (*Microula sikkimensis*) to at least 93 days (*Oxytropis falcata* and *Draba handelii*), except *Heracleum* sp. and *Saussurea* sp., whose flowering duration were the shortest and uncertain. *Androsace umbellata*, *Arenaria pulvinata*, *Potentilla parvifolia*, *Oxytropis falcata* and *Draba handelii* had the longest flowering durations, and were 61, 62+, 76+, 87+ and 93 days, respectively. No fruits were observed in *Ephedra sinica*, *Saussurea gnaphalodes*, *Potentilla parvifolia* and *Saussurea* sp. Twenty species began fruiting between early July and late August; 10 in July and 10 in August. *Draba handelii* was the first species to set fruit on 11 July and *Heracleum* sp. was the last on 21 August, an interval of 51 days. It was not possible to determine peak fruiting dates for six species (peak occurred after 23 August). All other species reached peak fruiting in August with the exceptions of *Sedum fischeri* (27 July) and *Draba handelii* (29 July).

3 Discussion

Species that live in seasonal environments have conflicting selection pressures on their phenology. In particular, those living at the high altitude at the Mt. Qomolangma base camp have to contend with stressful conditions characterized by prolonged periods of low winter temperatures along with brief, cool growing seasons and cold soils with low fertility and, often, low moisture.

These species are stress-tolerators (Grime 1977), have minimal vegetative growth and reproductive activity, and are poor competitors. Those that flower and fruit early have greater access to resources but are at a greater risk of environmental stresses, while those that flower and fruit later will reduce the probability of extreme environmental stress but may be faced with resource shortage and competition from neighbours. The degree of synchrony or asynchrony is under selective pressure both within a species and between species. In this study we considered only comparisons between different species and it was observed that 50% of plant species started flowering relatively early in May and June while others delayed until early July to mid-August, indicating a general pattern of early flowering among plants. This partially supports the argument that a dominant strategy of alpine species is early flowering because of the short growing season (Billings and Mooney 1968; Bliss 1971; Inouye and Pyke 1988; Totland 1993). However, this leaves unanswered why so many species delay flowering and fruiting, and why there was such wide variation in timing and duration of all phenological variables measured in this study. Both of these are likely due to evolutionary divergence to reduce competition for limited pollinators and resources during the short growing season in this region. Differences in flowering phenology in closely related sympatric species such as *Delphinium nelsoni* and *Ipomopsis aggregata*, may not only reduce competition for pollinators (Waser 1978), but also help ensure genetic isolation (Gentry 1974).

Both abiotic and biotic factors are likely to impose selection pressure on flowering phenology, and the phenology of any particular species will reflect many selective compromises. At the abiotic level, although species with earlier flowering can make more effective use of resources and reduce competition, they may not have adequate time to accumulate enough resources resulting in limited fruit production. Later-flowering species with a longer pre-fruiting growth period have the advantage of being able to accumulate more resources for fruiting, but face the double risk of not being able to use all of the accumulated resources before the end of the growing season (Simpson and Dean 2002; Komeda 2004; Weinig and Schmitt 2004), and of losing fruit in the event
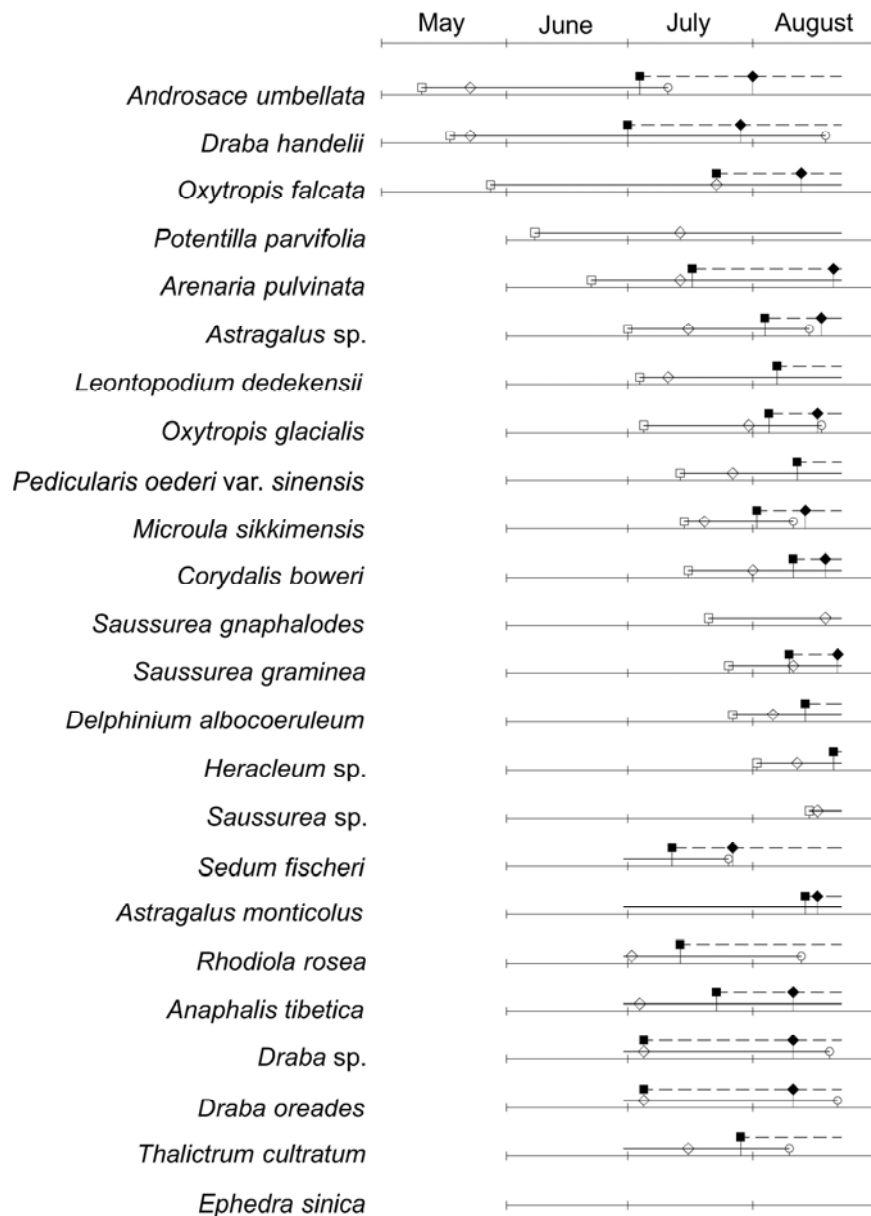
Figure 3 Flowering and fruiting phenology of 24 plant species in the base camp area of the north slope of Mt. Qomolangma, Tibet, western China. "□"represents first flowering date. "◇" represents peak flowering date. "○" represents last flowering date. "■" represents first fruiting date. "◆" represents peak fruiting date. Dark solid lines represent the flowering period. Dark dashed lines represent the fruiting period

of a premature end to the growing season because of changing environmental conditions; both have negative effects on reproduction, and ultimately on fitness. At the biotic level, one herbivore may attack early inflorescences, thus selecting for later flowering, while another may prefer later inflorescences, and thus favor early flowering (Evans et al. 1989). The patterns of early flowering and long flowering duration in some species, such as *Oxytropis falcata*, *Draba handelii* and

Potentilla parvifolia, etc., may account for their local dominance.

Many studies have reported a shortening of flowering duration at low-altitudes (Pojar 1974; Heinrich 1976; Opler et al. 1980; Lack 1982; Herrera 1986), yet others report no significant relation between flowering duration and altitude (Price and Waser 1998; Blionis et al. 2001). For 22 of the species monitored at the Mt. Qomolangma site, the duration of flowering ranged from 27 to 93
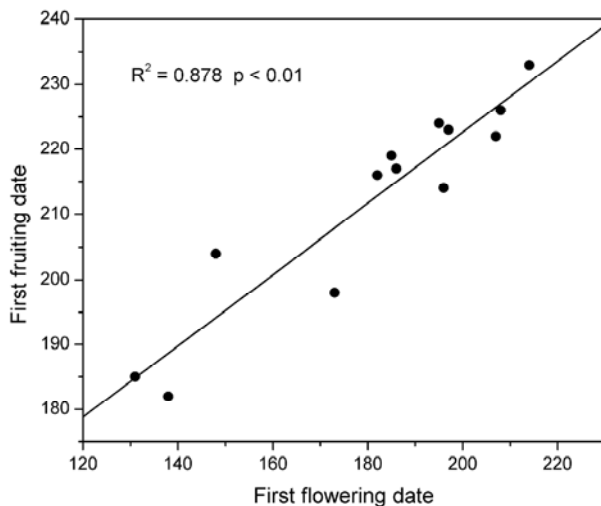
Figure 4 The relationship between the dates of first flowering and first fruiting. Axes scales are both the number of days from January 1st, 2005

days, averaging at least 47.8 days. This average value is much higher than the 20 days for an alpine community on Mt Olympus, Greece (Makrodimos et al. 2008) and the 23 days for a subalpine meadow in British Columbia (Pojar 1974). The duration of the flowering period at the north-facing 5,180 m Mt. Qomolangma site is more similar to habitats at much lower elevations such as 55 days in a Mediterranean ecosystem in Greece (Petanidou et al. 1995), and 30-80 days in a coastal shrubland in Spain (Herrera 1987). This asynchrony between variation of flowering duration and altitude suggests no uniform pattern of change for the duration of the flowering period in response to changes of elevation. Similarly, Blionis et al. (2001) did not detect any significant relationship between the duration of flowering and elevation. It is possible that duration of flowering is not determined by extrinsic factors, instead, it may be largely due to intrinsic factors (Parrish and Bazzaz 1979) such as 'ecological pollination syndromes' (Makrodimos et al. 2008). More research is required to unravel the underlying causes influencing this phenological feature, especially in extremely high alpine environments such as in the region of Mt. Qomolangma.

In alpine environments, the growing season is short, cool, and curtailed at both ends by sub-zero temperatures. This imposes major constraints on alpine biota and it has been suggested that time can be viewed as a resource for these species because the growing season is so compressed (Galen and Stanton 1991). These high alpine sites support mostly stress-tolerant species (Grime 1977) and their phenology is influenced by many factors, among which air temperature, sunlight and water are the most important (Puckridge and O'Toole, 1981; Hänninen 1990; Fukai 1999; Chmielewski and Rötzer 2001; Snyder et al. 2001; Zhang et al. 2001). Flowering has been reported to be optimal in spring due to good water availability, mild temperatures and high insect activity (Mooney et al. 1974; Baker et al. 1982; Kummerov 1983). But at the Mt. Qomolangma sites, the summer period (from June to August) has the most flowering and fruiting, and is also the period with highest precipitation and highest temperature. Both precipitation and temperature show an approximate synchrony, increasing from early May to late June and being at high levels from early July to late August, providing the most favorable conditions for the growth of alpine vegetation. Both precipitation and temperature decrease dramatically after early August, but at that time most plants species have already reached peak fruiting, indicating that species have evolved to fruit before the on-set of the harsher environmental conditions. Suitable climatic conditions are also beneficial to insect activity, such as bumblebees, which are major pollinating agents in the study area and generally restrict foraging to periods when ambient temperatures are above 10 °C (Heinrich 1976); typically from mid-May to early September.

The alpine climate puts severe constraints on life cycles and reproduction of alpine flora. The timing of flowering is particularly critical and may affect both breeding system and reproductive success (Thórhallsdóttir 1998). Early flowering lessens interspecific competition for limited resource availability and pollinator services, but earlier seed, as a result of earlier flowering, may lead to proportionally greater expenditure on reproductive tissue, possibly at the expense of vegetative or clonal growth (Wookey et al. 1995). The plant species observed in this study varied greatly in their phenological patterns, with some early flowering and fruiting while others were later. However, nearly half of the species in the community produced fruit relatively early (in July), and they also started flowering relatively early

(before July). The fact that so many species begin to flower and fruit almost synchronously is likely due to independent responses by the different species to the prevailing short-season condition, or could possibly be a cooperative or facilitative response among these alpine plants that ensures the continued presence of many species that are close to their abiotic limits of distribution.

For plant species living in severe and resource-deficient alpine environments, sexual reproduction is generally unreliable, and plants in such environments tend to have proportionately more asexual reproduction (Billings 1974; Eriksson 1997; Klimes et al. 1997). However, asexual reproduction alone will lead to a decrease in genetic diversity of plant populations and thereby reduce their ability to adapt to changing environmental conditions (Zhang and Zhang 2007). As a consequence, sexual reproduction may also be highly selected under harsh environments (Fabbro and Körner 2004). *Ephedra sinica* is an exception among all of our monitored plant species; it did not flower or fruit during the growing season. Many low-resource communities are dominated by stress-tolerant species (Grime 1977, 1979, 2002) and these typically have very low reproductive vigor and rely heavily on vegetative reproduction.

The onset of flowering is strongly affected by yearly climatic variability, and timing of flowering is sensitive to temperature changes (Makrodimos et al., 2008). Many authors have reported earlier flowering of alpine plants with simulated climate warming treatments (Alatalo and Totland 1997; Henry and Molau 1997; Stenström et al. 1997; Suzuki and Kudo 1997; Price and Waser 1998). Global warming may modify abiotic conditions that influence individual plant performance, with alpine and arctic ecosystems predicted to be particularly affected (Callaghan and Jonasson 1995; Guisan et al. 1995; Körner 1995, 1999). In the Mt. Qomolangma region with extremely high elevation, long-term weather patterns show a significant increasing trend for inter-annual variation in air temperature. It is hypothesized that with continued global warming, most of the plant species in this region will flower earlier than at present, which is partially consistent with patterns reported for a Mediterranean community (Petanidou et al. 1995).

Phenological observation in alpine environments with extremely high altitudes is a long-standing challenge. This was a preliminary observational study done to provide a benchmark against which to monitor change over the following years. Future measurements will allow comparisons of phenological responses to be made for members of the same species living in adjacent areas. An experimental approach, focusing on phenological variability of local plant species in different microenvironments under the combined influences of biotic and abiotic factors, is required to formally test their effects on phenology patterns.

Acknowledgments

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