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ORIGINAL ARTICLE

Koichi Takahashi · Yohei Tokumitsu · Koh Yasue

Climatic factors affecting the tree-ring width of *Betula ermanii* at the timberline on Mount Norikura, central Japan

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Abstract Tree-ring-width chronology of *Betula ermanii* was developed at the timberline (2,400 m a.s.l.) on Mount Norikura in central Japan, and climatic factors affecting the tree-ring width of *B. ermanii* were examined. Three monthly climatic data (mean temperature, insolation duration, and sum of precipitation) were used for the analysis. The tree-ring width of *B. ermanii* was negatively correlated with the December and January temperatures and with the January precipitation prior to the growth. However, why high temperatures and heavy snow in winter had negative effects on the growth of *B. ermanii* is unknown. The tree-ring width was positively correlated with summer temperatures during June–August of the current year. The tree-ring width was also positively correlated with the insolation duration in July of the current year. In contrast, the tree-ring width was negatively correlated with summer precipitation during July–September of the current year. However, these negative correlations of summer precipitation do not seem to be independent of temperature and insolation duration, i.e., substantial precipitation reduces the insolation duration and temperature. Therefore, it is suggested that significant insolation duration and high temperature due to less precipitation in summer of the current year increase the radial growth of *B. ermanii* at the timberline. The results were also compared with those of our previous study conducted at the lower altitudinal limit of *B. ermanii* (approximately 1,600 m a.s.l.) on Mount Norikura. This study suggests that the climatic factors that increase the radial growth of *B. ermanii* differ between its upper and lower altitudinal limits.

Keywords *Betula ermanii* · Climatic conditions · Dendrochronology · Timberline · Tree-ring-width chronology

K. Takahashi · Y. Tokumitsu
Department of Biology, Faculty of Science, Shinshu University, Matsumoto, Nagano 390-8621, Japan

K. Yasue
Department of Forest Science, Faculty of Agriculture, Shinshu University, 8304 Minami-Minowa, Nagano 399-4598, Japan

Present address: K. Takahashi (✉)
Department of Biology, McGill University, 1205 Docteur Penfield, Montreal, QC H3A 1B1, Canada
E-mail: koichit@gipac.shinshu-u.ac.jp
Tel.: +1-514-3984116
Fax: +1-514-3985069

Introduction

Timberlines offer the most severe climatic conditions, including low temperature, strong winds and short growing season, for plants along altitudinal gradients, and therefore, the regeneration of trees at the timberlines is believed to be sensitive to climatic changes (e.g., Briffa and Osborn 1999; Kusnierczyk and Ettl 2002; Lloyd and Fastie 2002; Chapin et al. 2004; Daniels and Veblen 2004; Dullinger et al. 2004). For example, some researchers have discussed that heavy seedling establishment occurred in warmer and/or more mesic years near the timberlines (Kullman 1986; Taylor 1995; Kajimoto et al. 1998; Camarero and Gutiérrez 1999; Gervais and MacDonald 2000). In addition, many dendrochronological studies have revealed that radial growth of trees near the timberlines increased in milder years with higher temperatures than average (Ettl and Peterson 1995; Gostev et al. 1996; Buckley et al. 1997; Peterson and Peterson 2001; Wilson and Hopfmueller 2001). Trees may respond to climatic conditions more quickly in growth than in seedling establishment. Thus, growth is a useful indicator to examine how climatic conditions affect regeneration of trees at the timberlines. Although many researchers have investigated the effects of climatic conditions on tree growth at timberlines in North America and Europe (e.g., Kienast et al. 1987; Rolland et al. 1998; Szeicz and MacDonald 1995; Paulsen et al. 2000; Carrer and Urbinati 2004), there are few studies reported in Japan. Increased knowledge of the climate–growth relationships at timberlines is of great importance for understanding the effects of global warming on tree regeneration at timberlines, especially in Japan, where there are many high mountains.

Betula ermanii Cham., a deciduous broad-leaved tree species, is widely distributed in subalpine coniferous forests in Japan (Tatewaki 1958; Miyawaki 1985). *B. ermanii* dominates over coniferous species in the upper zone of subalpine coniferous forests, and often forms pure stands near the timberlines. Therefore, *B. ermanii* is one of the representative tree species at timberlines in Japan. Takahashi et al. (2003) examined the effects of climatic conditions on the tree-ring width of *B. ermanii* at its lower altitudinal limit on Mount Norikura in central Japan. They suggested that lower precipitation combined with high temperatures in the hottest month of August reduced the tree-ring width of *B. ermanii*. Climatic conditions change with altitude, i.e., air temperature is lower and precipitation is greater at a higher altitude. Therefore, it is expected that climatic factors affecting the tree-ring width of *B. ermanii* will also differ between the lower altitudinal limit and the timberline (i.e., the upper altitudinal limit). However, there are no studies that compare the growth responses of *B. ermanii* to climatic conditions at its upper and lower altitudinal limits.

The purpose of this study was to examine which climatic factors affect the tree-ring width of *B. ermanii* at the timberline on Mount Norikura in central Japan using the dendrochronological technique. We also compared the results of this study with those of our previous study (Takahashi et al. 2003), conducted at the lower altitudinal limit of *B. ermanii* on Mount Norikura.

Materials and methods

Study site

This study was carried out on Mount Norikura (36°06′N, 137°33′E, 3,026 m a.s.l.) in central Japan. *B. ermanii* and four conifers (*Abies veitchii* Lindl., *Abies mariesii* Mast., *Picea jezoensis* var. *hondoensis* Rehder, and *Tsuga diversifolia* Mast.) were dominant between approximately 1,600 and 2,500 m a.s.l. in the subalpine zone. *B. ermanii* dominated over the four conifers in the upper zone of the subalpine coniferous forests. Alpine dwarf pine scrub (*Pinus pumila* Regel) was distributed above the subalpine zone (Takahashi 2003a). In this study, the timberline was defined as the boundary between the subalpine zone dominated by tall trees and the alpine zone dominated by dwarf pine.

The study site was located at about 100 m below the upper edge of the timberline in elevation (2,400 m a.s.l.) on the east slope of Mount Norikura. This slope was the same as that on which our low altitudinal study site (1,600 m a.s.l.) was located (Takahashi et al. 2003). The horizontal distance between the two study sites was 4.5 km. Trunk height of canopy trees ranged between 10 and 15 m. Mean annual temperature at this study site was estimated to be 0.1°C from the temperature recorded at Nagawa Weather Station (1,068 m a.s.l., approximately 11 km from the study site) using the standard lapse rate of −0.6°C for each +100 m altitude. Mean monthly temperatures in the coldest month of January and the hottest month of August were estimated to be −11.5 and 12.3°C, respectively.

Sampling and measurement

Nineteen trees were cored from stems at breast height (1.3 m), with two cores from each tree, during July–August 2002. From one of the 19 trees only one core was sampled (i.e., total 37 cores were sampled). Stem diameter at breast height was measured for each tree. All cores were dried, mounted, sanded, and then the tree-ring widths were measured at a precision of 0.01 mm under a microscope by using a sliding measurement stage (TA Tree-Ring System, Velmex, NY, USA) linked to a computer. The tree-ring boundaries of *B. ermanii* were distinguishable by the small-diameter cells (terminal parenchyma).

Chronology development

All cores were cross-dated visually by matching characteristic wide and narrow rings that were synchronous within sample trees. Visual cross-dating was statistically verified by using the COFECHA program (Holmes 1983, 1994), which tests each individual series against a master dating series (mean of all series) on the basis of correlation coefficients. Of 37 cores, five cores that had low correlations with other cores were eliminated from further analyses.

Growth of trees is affected not only by climatic factors but also by age, disturbance and competition between neighboring trees. To reduce variations caused by such non-climatic factors, all raw ring-width series were standardized by fitting smoothing splines (Cook and Peters 1981) with a 50% frequency-response cutoff of 40 years. This procedure was done using the ARSTAN program (Cook 1985; Holmes 1994). After standardizing each individual series, the tree-ring-width chronology of *B. ermanii* was obtained by averaging the standardized individual series in each year. We used at least five cores to make the tree-ring-width chronology in each year.

Statistical analysis

Climatic factors affecting the tree-ring width of *B. ermanii* were investigated. Three monthly climatic data were used for the analysis (mean temperature, insolation duration, and sum of precipitation). The nearest weather station to the study site was Nagawa (1,068 m a.s.l., approximately 11 km from the study site). However, the available meteorological data at Nagawa was rather limited as observation started there in 1979. A long-term record was available at Matsumoto (610 m a.s.l., approximately 40 km from the study site). The available meteorological data at Matsumoto began in 1898 for temperature and precipitation, and in 1899 for insolation duration. The correlations of climatic data between the two stations were highly significant (Takahashi et al. 2003). Thus, we used the long-term climatic data recorded at Matsumoto.

Relationships between climate and tree-ring width were analyzed using a simple correlation analysis. The analysis was done using the climatic data from the start of the previous growing season to the end of the current growing season because the growth of many tree species is affected not only by the climatic conditions of the current year but also by those of the previous year (cf. Fritts 1962; Sano et al. 1977; Okitsu 1988; Eshete and Ståhl 1999; Takahashi et al. 2001; Speer et al. 2004). The approximate growing season at this study site (2,400 m a.s.l.) was estimated to be June–September because the mean monthly temperatures exceeded 5°C, effective heat for plant growth (Kira 1948), during this period. Thus, the simple correlation analysis was performed using the climatic data from June of the previous year to September of the current year (16 months in total) for the period 1900–2001 ($n = 102$).

Results

Of 19 trees (37 cores) of *B. ermanii*, 17 trees (32 cores) were successfully cross-dated, and were used to develop a master chronology with good correlations between trees (Table 1). The span of the tree-ring-width chronology of *B. ermanii* was 172 years (Table 1, Fig. 1). The first-order autocorrelation, as a measure of the influence of the previous year's growth on growth in the current year, was 0.34 (Table 1). The mean sensitivity and standard deviation (SD) as measures of interannual variation in tree-ring width were 0.23 and 0.25, respectively (Table 1). These values were higher than those of *B. ermanii* at its lower altitudinal limit (approximately 1,600 m a.s.l.) of this mountain, where the mean sensitivity and SD were 0.13 and 0.11, respectively. The mean correlation coefficient between *B. ermanii* individual trees at the timberline was also higher than that at the lower altitudinal limit (0.41 vs. 0.13, Table 1). These differences in the basic statistics between the two sites indicate that *B. ermanii* grew more synchronously, and the interannual variation in the tree-ring width was higher at the timberline than at the lower altitudinal limit on Mount Norikura. It is likely that the severe climatic conditions were reflected in these growth traits at the timberline. Furthermore, the tree-ring-width indices were not significantly correlated between the timberline and the lower altitudinal limit of *B. ermanii* for the period 1943–2000, which corresponded to the span of the chronology in the lower altitudinal limit ($r = 0.17$, $P = 0.20$, $n = 58$, Fig. 1). The difference in growth patterns between the timberline and the lower altitudinal limit appears to reflect the influence of distinct climatic factors on the tree-ring width of *B. ermanii*.

Correlation coefficients indicate that temperatures of several months were significantly correlated with the tree-ring-width index of *B. ermanii* at the timberline (Fig. 2). December and January temperatures prior to growth were negatively correlated with the tree-ring-width index ($P < 0.05$, Fig. 2). January precipitation prior to growth also showed a negative correlation. During the growing season, the current-year summer temperatures from June to August were positively correlated with the tree-ring-width index ($P < 0.05$, Fig. 2). The tree-ring-width index was also positively correlated with the July insolation duration in the current year ($P < 0.05$, Fig. 2). In contrast, the tree-ring-width index was negatively correlated with the current-year summer precipitation from July to September ($P < 0.05$, Fig. 2). However, these negative correlations of summer precipitation do not seem to be independent of temperature and insolation duration because of the inverse relationships of precipitation with temperature and with insolation duration during the growing season, except for September temperature (Table 2).

Table 1 Basic statistics of tree-ring-width chronology for *B. ermanii* at the timberline on Mount Norikura in central Japan

Statistics	Value
Number of trees (cores)	17 (32)
Range of DBH[a] (cm)	19–41
Range of chronology (years)	172
Mean tree-ring width (mm)	0.65
Standardized chronology	
Mean sensitivity	0.23
Standard deviation	0.25
First-order autocorrelation	0.34
Mean correlation between trees[b]	0.41
Signal-to-noise ratio[b]	10.22

[a] Stem diameter at breast height
[b] Calculated for a common interval from 1891–1997

Discussion

The correlation analysis showed that the tree-ring width of *B. ermanii* was negatively correlated with December and January temperatures and with January precipitation prior to growth. However, the underlying mechanism that caused high temperatures and heavy snow in winter to have negative effects on the tree-ring width of *B. ermanii* is unclear. The correlation analysis showed positive correlations with summer temperatures and insolation duration and the negative correlations with summer precipitation in the current year. However, it is difficult to consider that heavy precipitation in summer caused diameter growth reduction of *B. ermanii* by providing too much soil water. Taking into account the

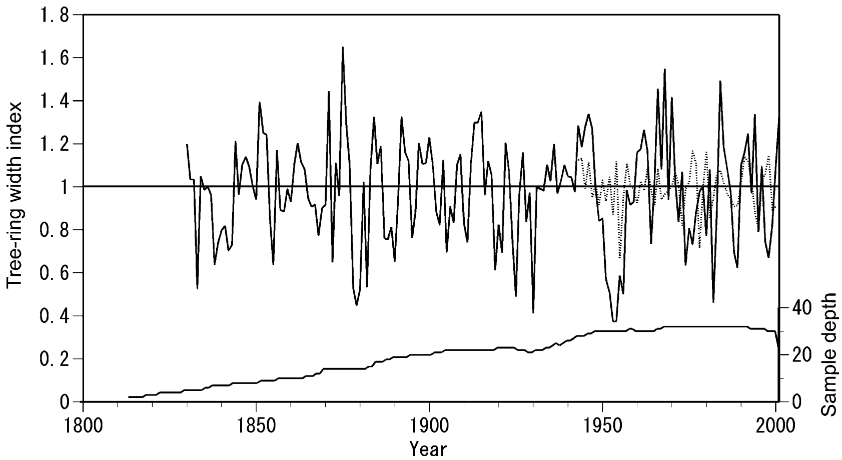

Fig. 1 Standardized tree-ring-width chronology and sample depth of *B. ermanii* at the timberline on Mount Norikura in central Japan (*solid lines*). The chronology was constructed using at least five cores in each year. The *dotted line* indicates the standardized tree-ring-width chronology of *B. ermanii* (since 1943) at its lower altitudinal limit (*redrawn* from Takahashi et al. 2003)

negative correlations of precipitation with insolation duration and temperature, it is plausible that the tree-ring width of *B. ermanii* at the timberline was decreased by low insolation duration and low temperature due to frequent rain events in the summer of the current year.

Precipitation associated with cloud cover decreases light energy and air temperature, which in turn brings about a reduction in the photosynthetic production of plants in mesic regions. Although most dendrochronological and/or dendroclimatological studies have not examined the effects of insolation duration on the tree-ring width, many researchers reported that tree growth was limited by low summer temperatures at high altitudes and high latitudes (Oberhuber et al. 1997; MacDonald et al. 1998; Gervais and MacDonald 2000; Mäkinen et al. 2000; Grudd et al. 2002; Helama et al. 2002; Kirdyanov et al. 2003; Takahashi 2003a; Barber et al. 2004). Low temperatures reduce tree growth in several ways. Photosynthetic rates of plants are generally temperature dependent, and therefore, low temperatures during the growing season reduce photosynthetic production for alpine and subalpine plants (DeLucia and Smith 1987; Körner 1999). Latewood development is also reduced under low temperature conditions (Gindl 1999). Furthermore, Gostev et al. (1996) and Solomina et al. (1999) showed that early summer temperatures in the current year were positively correlated with the tree-ring width of Dahurican larch (*Larix cajanderi* Mayr.) in the Kamchatka Peninsula, in the Russian Far East. Growth periods for plants are rather short at timberlines or high elevations. High temperatures in early summer are effective for tree growth by prolonging the duration of growing season (Camarero et al. 1998). This view is also supported in this study because of the positive correlation of the tree-ring width of *B. ermanii* with temperature in June, i.e., the start of the growing season. It is believed that the growth of *B. ermanii* strongly depends on the current year's photosynthetic production (Kikuzawa 1983). Therefore, the growth of *B. ermanii* is apt to be affected by the current year's climatic conditions (Takahashi et al. 2003). Accordingly, it is no doubt that less insolation duration and low temperatures due to frequent rain events in summer of the current year reduce the tree-ring width of *B. ermanii* at the timberline.

The results of this study are different from those of our previous study (Takahashi et al. 2003), conducted for *B. ermanii* at the lower altitudinal limit (1,600 m a.s.l.) on Mount Norikura. Takahashi et al. (2003) suggested that less precipitation combined with high temperatures in the current-year August (i.e., drought stress) reduced the tree-ring width of *B. ermanii* at its lower altitudinal limit. August is the hottest month, but precipitation in this month is lower compared with other summer months (Takahashi et al. 2003). Although Takahashi et al. (2003) did not analyze the effect of insolation duration on tree-ring width, a marginally significant negative relationship was detected between the tree-ring width and the insolation duration in August of the current year in their data set ($r = -0.26$, $P = 0.053$, $n = 58$). This negative relationship supports that growth of *B. ermanii* is reduced by drought stress at its lower altitudinal limit. The discrepancy between the results of this study and those of Takahashi et al. (2003) is apparently due to the difference in climatic conditions between the two sites at different altitudes. Precipitation is greater at a higher altitude in this region, which is associated with a decrease in air temperature (Nagano Meteorological Observatory 1998). In addition, fog often occurs on summer afternoons at high altitudes in central Japan. Such local-scale climatic conditions would hardly cause water stress for *B. ermanii* at the timberline (Takahashi 2003b), but would reduce photosynthetic production by reducing light energy and temperature. Fujiwara et al. (1999) reported that the tree-ring width of *A. mariesii* was positively correlated with summer temperatures at about 2,000–2,200 m a.s.l. on Mount Norikura, and suggested that the reduction in tree growth during cool summers was due to insufficient light energy. Therefore, the negative effects of less insolation duration and low temperatures on the growth of *B. ermanii* are believed to be more significant near its upper altitudinal limit or the timberline, while lower

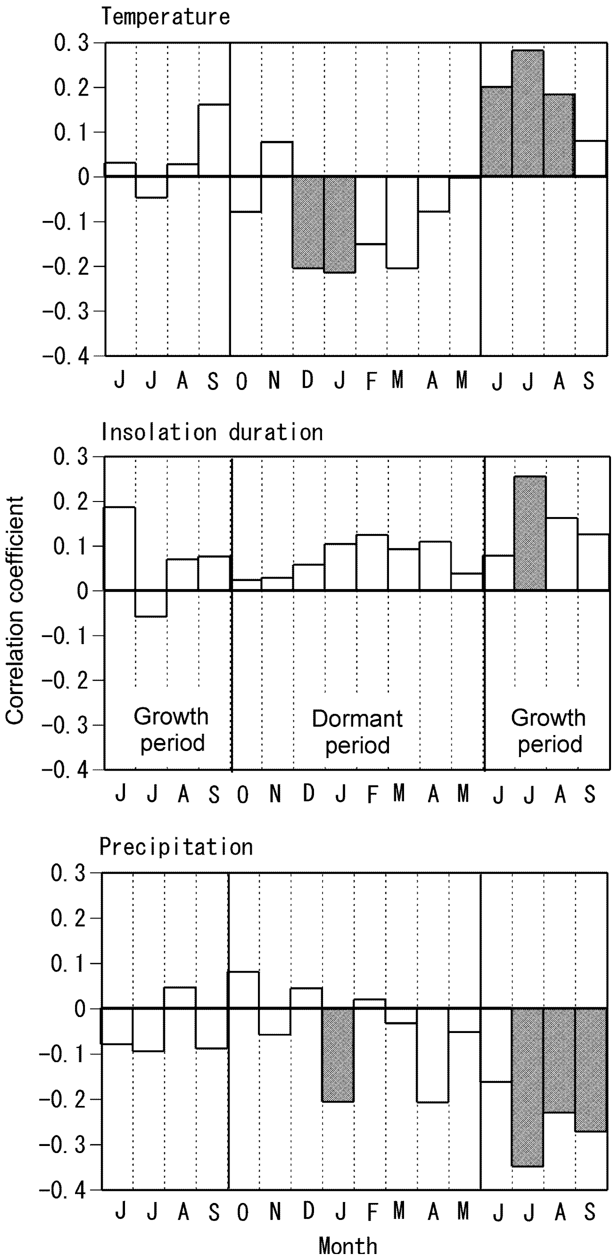

Fig. 2 Results of the simple correlation analysis for the relationships between the standardized tree-ring-width chronology of *B. ermanii* and monthly climatic data (mean temperature, insolation duration, and sum of precipitation). Significant relationships ($P < 0.05$) are indicated by *shaded bars*

Table 2 Correlation coefficients of monthly sum of precipitation with monthly mean temperature and with monthly insolation duration at Matsumoto Weather Station in central Japan, during the 4-month growing season 1900–2001 ($n = 102$)

Month	Temperature	Insolation duration
June	−0.20*	−0.56**
July	−0.52**	−0.61**
August	−0.47**	−0.42**
September	−0.078	−0.67**

*$P < 0.05$, **$P < 0.001$

precipitation with high temperatures in the hottest month of August reduces the growth of *B. ermanii* near its lower altitudinal limit.

Several researchers also reported that a major climatic factor enhancing tree growth at low altitudes was summer precipitation, but at high altitudes in boreal forests and in subalpine forests it was summer temperatures (Ettl and Peterson 1995; Buckley et al. 1997; Peterson and Peterson 2001; Wilson and Hopfmueller 2001; Mäkinen et al. 2002). Across a latitudinal gradient, Lara et al. (2001) also showed that the tree-ring width of *Nothofagus pumilio* (Poepp et Endl.) Krasser was positively correlated with summer precipitation and negatively with summer temperature at its northern distribution limit in the central Andes of Chile in the southern hemisphere, while the summer precipitation had negative effects on the tree-ring width at its southern distribution limit. They described that high temperatures in summer reduced the soil water availability for *N. pumilio* at the northern distribution limits by enhancing evapotranspiration. Therefore, it is suggested that the climatic factors limiting tree-ring width are different along altitudinal and latitudinal gradients, as found for *B. ermanii* in this study.

We presented the first tree-ring-width chronology of *B. ermanii* at the timberline, and we concluded that climatic factors increasing the tree-ring width of *B. ermanii* changed from heavy precipitation in the hottest month of August at its lower altitudinal limit to high insolation duration and high temperatures due to less precipitation in summer at its upper altitudinal limit (i.e., the timberline). Thus, the growth of *B. ermanii* along the altitudinal gradient cannot be predicted by temperature alone even under a scenario of global warming. Global circulation models predict that climatic change due to CO_2 doubling increases annual mean temperature by about 4–6°C and precipitation by about 10–15% in east Asia including Japan (Uchijima and Ohta 1996). Therefore, the expected climatic changes may have both positive and negative effects on the growth of *B. ermanii*: precise prediction of the effects of global warming on tree growth along the altitudinal gradient still remains uncertain. Further studies are necessary to comprehensively predict how global warming causes changes in local weather patterns and then affects growth of *B. ermanii* along the altitudinal gradient.

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