Effects of climate on the tree ring density and weight of *Betula ermanii* in a cool temperate forest in central Japan

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Abstract

Key Message **The tree ring weight of Betula ermanii was primarily controlled by the ring width, butnot by its ring density. The climate responses of them were clarified by dendrochronologicalanalysis.**

Abstract Global warming scenarios have made the understanding of carbon sequestration changes in the stems of forest trees important. However, there is a lack of understanding about climate change's effects on the wood density of hardwood, which is a crucial indicator of wood biomass. Therefore, we investigated the effects of climatic factors on the ring density and ring weight of *B. ermanii,* a dominant tree species in cool temperate regions and subalpine regions of Japan. We calculated the annual ring weight growth by multiplying the ring width and density. We developed the residual chronologies of the ring density and weight and performed a correlation analysis between the chronologies and the climate data. We deduced that the ring density was independent of the ring width for individual cores. The ring weight chronology showed a positive correlation with the ring width but not with ring density. The ring density decreased due to higher temperature, long sunshine duration, and less precipitation from mid-July to early October in the previous year. Conversely, those from mid-June to mid-August increased the ring density in the current year. The previous year's high nighttime temperature in autumn and dry conditions during the current year's summer decreased the ring weight, similar to the climate responses of ring width. Therefore, we concluded that ring weight was not controlled by ring density, but majorly regulated by ring width. Conclusively, this study's results can evaluate the impact of climate change on the carbon sequestration potential of the stem of *B. ermanii*.

Keywords *Betula ermanii* · Climate response · Dendrochronology · Tree-ring

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Introduction

Climate change, such as the temperature rise, has been predicted as the result of global warming (IPCC 2014). In Japan, an increase in the annual mean temperature of about 2 °C was observed from 1898 to 2018 (Japan Meteorological Agency 2018). Under global warming scenarios, forest is a key component of the carbon cycle, and the stems of trees sequester large amounts of carbon (Roy et al. 2001), making their radial growth one of the major sources of long-term carbon fixation. Thus, understanding the influences of climatic factors on the radial growth of trees became important to accurately predict the impact of climate change.

In Japan, 67% of the total land area is forest, and about half of the forests are natural, with 82% of the natural forests being dominated by hardwood species (Japan Forestry Agency 2012). Among the natural forests, the cool temperate forest is widely distributed in the northern part of the main island and the mountainous regions of the central part

of the main island (Japan Forestry Agency 2019). Clearing the relationships between the radial growth of the dominant tree species in the cool temperature forest and climatic factors can be useful for forecasting their carbon sequestration potential. *Betula ermanii* is a widespread deciduous broad-leaved species in cool temperate regions to subalpine regions, which is distributed in Hokkaido island and the mountains of northern part of the main island in Japan (Miyawaki 1985). Evaluating the effects of climate on the radial growth of *B. ermanii* is important to understand the carbon sequestration changing in cool temperature forest under global warm scenarios. The dendrochronological technique is a useful method for evaluating the effects of climate on tree growth (Fritts 1976; Schweingruberm 1996; García-Suárez et al. 2009). Positive correlations were observed between summer temperatures and ring widths of *B. ermanii* at higher altitudes or higher latitudes of its distribution range (Takahashi et al. 2005; Wang et al. 2013; Deck et al. 2017). At the lower altitudinal limits of the distribution range, there is a positive correlation between ring width and precipitation, and a negative correlation with the temperature in summer (Takahashi et al. 2003; Shen et al. 2020).

Alternatively, only ring width is insufficient for evaluating the relationship between radial growth and carbon sequestration, and the density of wood is an important parameter to determine carbon sequestration in the stem (Fujiwara 2007). Annual ring density can be measured using soft X-ray densitometry (Polge 1970; Parker 1970), which has been used as indicators of the climate reconstruction in dendrochronological studies (Schweingruber et al. 1993; Yasue et al. 1994; Briffa et al. 1995; Briffa et al. 2013). The ring weight can be calculated using ring width and density (Hirano et al. 2020), which can also be used as the fundamental indicator of carbon sequestration in the stem. Thus, clarifying interrelations between ring width, ring density, and ring weight, in addition to analyzing their responses to climatic conditions, can provide important information on the changes in carbon sequestration in the stem according to climate change.

In the previous dendrochronological studies, monthly climate data were used to investigate the effects of climate factors on radial growth (e.g., Fritts 1976; Schweingruber 1988, 1996). The climate responses of trees do not necessarily follow the monthly calendar. Moving window correlation on daily climate data has been used in past dendrochronological reports (Beck et al. 2013; Árvai et al. 2018). Recently, correlation analysis between chronologies and moving averages of climate data stepped at short days interval have been demonstrated to be effective in revealing the clim ate response of tree rings concerning phenological changes (Shen et al. 2020; Hirano et al. 2020, 2021). The moving correlation analysis at short days interval can be helpful to better understand which climate factors affect ring density and ring weight change and at what timescales.

In the present study, we focused on diffuse porous *B. ermanii* in a cool temperate forest in central Japan, which is their lower altitudinal distribution limit. The study's objectives were to: (1) investigate the relationship between the series of ring density and ring width on ring weight; and (2) identify the climate response to ring density and ring weight using the dendrochronological technique and a moving average of meteorological data. Our findings reveal what climatic factors affect carbon sequestration in the stem of *B. ermanii*, and they can be used to predict the carbon sequestration potential of this species under climate change scenario.

Materials and methods

Study site

The study site was located on the northwestern slope of Mt. Norikura in central Japan (36°08′ N, 137°25′ E). This site is a cool temperate deciduous broadleaf forest at 1420 m a.s.l. It belongs to the TKY site of Gifu University, which is one of the core research sites of the AsiaFlux research network under the FLUXNET research network, and it is a site of Japan Long-Term Ecological Research Network under International Long-term Ecological Research Network. The forest canopy is predominated by *Betula ermanii* cham, *Quercus crispula* Blume, *Betula platyphylla* Sukatchev var. *japonica* Hara, and *Fagus crenata* Blume; and the understory is dominated by an evergreen dwarf bamboo, *Sasa senanensis* (Fr. & Sav.) Rehder. The snow from December to April also covered the site. Also, a rainy season began from mid-June to late July because of the Asian monsoon influence. After the rain season, the temperatures increase toward the summer highs. The year's highest temperatures were recorded in July and August (Fig. 1). The altitude of the site is the lower distribution limit for *B. ermanii*.

Tree ring data

We investigated 27 *B. ermanii* trees, which dominated the forest canopy. Shen et al. (2020) reported ring-width records of the trees. Two increment cores of 5 mm diameter were extracted from each sample tree at breast height. Then, we performed hot-water extraction for 3 days and extraction with a mixture of ethanol and toluene (1:2) for 3 days. Increment cores were cut transversely into strips that were 1.6 mm-thick using a twin-bladed saw. The strips were air-dried and subjected to X-ray analysis (Softex Co., Tokyo). The resultant radiographs were scanned at 2400 dpi on a scanner (EPSON GT-X970, Epson, Nagano, Japan). Ring width and ring density were obtained using the program
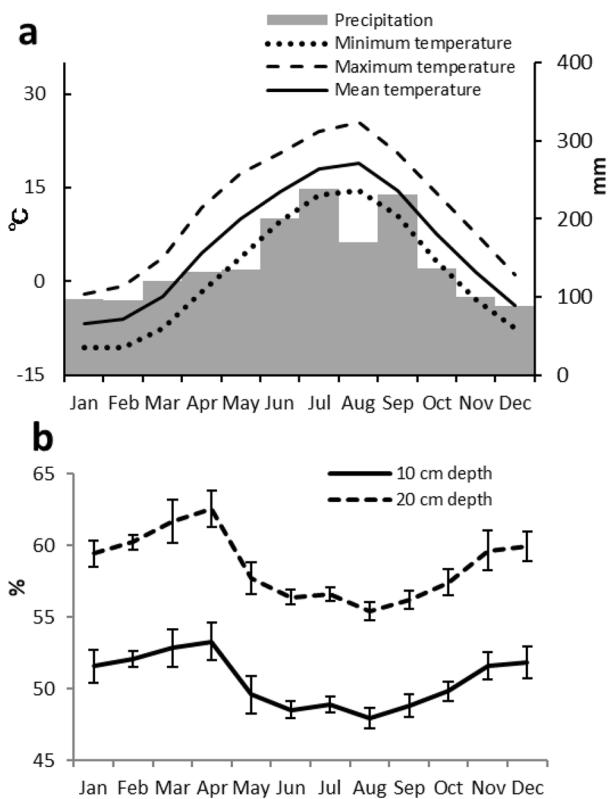
Fig. 1 The climate data of the study site.) Monthly precipitation and temperatures from 1961 to 2013. The temperature at 1420 m a.s.l. was calculated from the difference in altitude from the Takayama meteorological station (https://www.jma.go.jp/jma/index.html) with a temperature lapse rate of 0.568 °C/100 m (Ueno et al. 2013). **b** The monthly average soil water content from 2012 to 2017 was measured at the Takayama field station of the River Basin Research Center, Gifu University (http://www.green.gifu-u.ac.jp/takayama/)

WinDENDRO 2009b (Regent Instruments Inc., Quebec, Canada). Calculating the product of raw ring width and ring density enabled the estimation of the series of ring weight (Hirano et al. 2020). The raw ring width series were cross-dated in our previous report (Shen et al. 2020). The series of ring densities and ring weights were standardized using a cubic smoothing spline (Cook and Peters 1981) with a cutoff of 32 years. We performed Pearson's correlation analysis on the raw and standardized series between the ring width and density. Furthermore, we transformed the standardized series into a residual series using pooled autoregressive modeling to remove the effects of autocorrelation (Cook 1985). Residual chronologies for ring density and ring weight were developed using averaging of the individual residual series using a biweight robust mean (Cook and Kairiukstis 1990). The expressed population signal (EPS; Briffa and Jones 1990) was used to evaluate the chronology quality by calculating a 41-year moving window with a 1-year lag. EPS values > 0.85 were used as a threshold representing the reliable part of the chronologies (Wigley

et al. 1984). Lastly, statistical analyses of the developing chronologies were performed using the dlpR program (Bunn 2008) in the R environment (R Development Core Team; version 4.0.0). Multiple regression analysis was performed among ring width and density chronologies, with the ring weight as the dependent variable.

Climate response analysis

We used the daily meteorological data (mean, maximum, and minimum temperatures, precipitation and sunshine duration) from Takayama Meteorological Station (36°09′ N, 137°15′ E, 560 m a.s.l.), the Japan Meteorological Agency (https://www.jma.go.jp/jma/index.html) which is located 15 km west from the study site. The daily meteorological record was available from 1961, and we used 53 years from 1961 to 2013 as a time period for our analysis. The daily variation in meteorological data between the meteorological station and the study site was nearly the same (Nagai et al. 2013). Pearson's correlation analysis was conducted between the residual chronologies and a moving average of 31 days of meteorological data with a 1-day lag (Shen et al. 2020) using the R software environment (R Development Core Team; v.4.0.0). The analysis period was from May 16 of the previous year to November 15 of the current year. This period corresponds from the leaf exhibition of the previous year to the leaf fall of the current year.

Results

Measurement and standardized series

We excluded the cores with unclear images of X-ray due to deviation in fiber direction, which did not correspond with the X-ray direction. The data from 26 trees (38 cores) of *B. ermanii* were successfully used in the study (Fig. 2). The raw ring density increased slightly with age (Fig. 2a).

Based on the correlations between the raw ring width and ring density, 29% of cores showed a negative correlation ($p < 0.05$), and 10.5% of cores were positively correlated ($p < 0.05$; Fig. 3a). There were 10 trees that have 2 cores. Among these trees, 1 pair showed both significant negative correlations between ring width and ring density, 3 pairs showed significant negative or positive correlation for one core, 1 pair showed opposite significant correlations, and 5 pairs showed both no correlation. For the standardized series, excluding age-related trend, 31.6% of cores showed a negative correlation between ring density and ring width ($p < 0.05$), whereas 2.6% showed a positive correlation ($p < 0.05$; Fig. 3b).

Fig. 2 Raw tree ring density **a**) and weight series **b**). Bold lines incate the average of all series. The ring weight was calculated by multiplying raw ring width and density
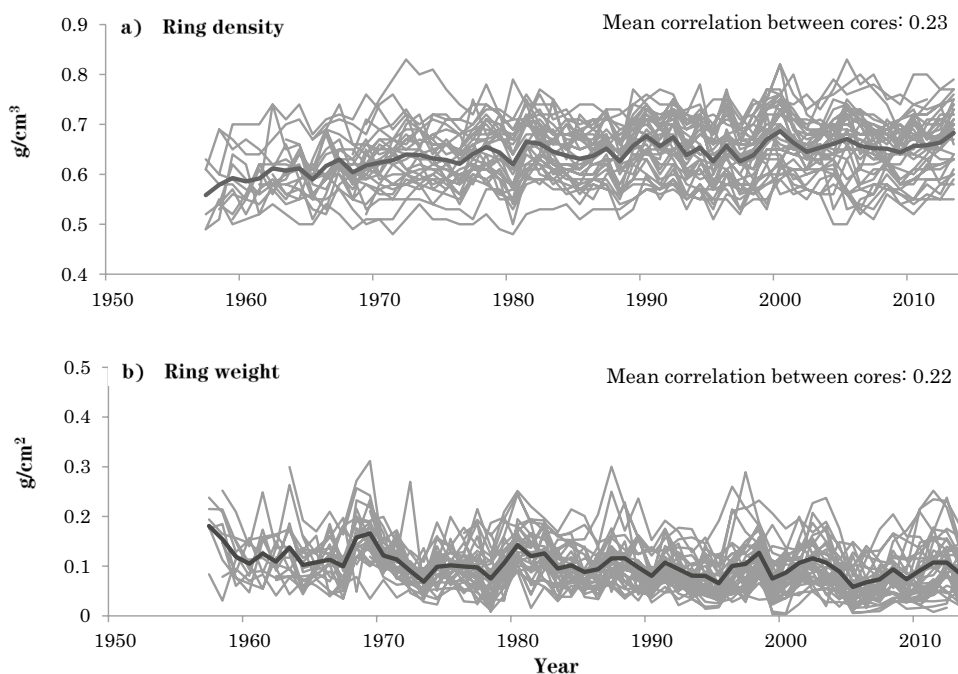
Chronologies

The ring density and the ring weight residual chronologies were developed (Fig. 4). The spans of both chronologies were 57 years. The mean correlations between trees estimated for the residual series for all possible pairs of individuals for ring density and ring weight were 0.23 and 0.23, respectively (Table 1). The common period for both chronologies with EPS exceeding 0.85 was from 1957 to 2013. We also used the chronologies and the meteorological data from 1962 to 2013 (51 years) for subsequent analyses, which is when the daily meteorological data records of Takayama were available.

Among the chronologies, a weak negative correlation was observed ($r = -0.31$; $p < 0.05$) between ring width and ring density (Fig. 5a). A strong positive correlation ($r = 0.99$; $p < 0.001$) between ring weight and ring width (Fig. 5b), whereas the ring weight and ring density chronologies (Fig. 5c) showed no significant correlation. The multiple regression model described 98% of the variation of the ring weight (Table 2). The p value of the F test is significant at 0.01. The partial correlations between the ring width and density showed a significant level, respectively. Pearson's correlation and multiple regression analysis revealed that the ring width significantly affects the ring weight, whereas the ring density has little effect on the ring weight.

Climate response

Seasonal changes in climate responses in shown in Fig. 6. The ring density chronology showed a negative correlation with temperature and sunshine duration and a positive correlation with precipitation in the previous summer. Conversely, the ring density chronology negatively correlated with spring and summer precipitation and positively correlated with summer and autumn temperature and summer sunshine duration in the current year. Additionally, the ring weight chronology was negatively correlated with the minimum and mean temperatures in the previous autumn, positively correlated with spring and summer precipitation, and negatively with summer temperature and sunshine duration in the current year.

Some responses of ring density are nearly opposite from those for ring width, which showed a negative correlation with sunshine duration in the previous summer and precipitation in the current spring and summer, as well as a positive correlation with the maximum temperature and sunshine duration in the current summer (Shen et al. 2020, Fig. 6). Approximately one-month lag was observed in the periods with a significant correlation in the climatic factors between ring density and ring width during the current summer; the overlap period was from mid-July to mid-August. However, the other climate responses to the previous summer,
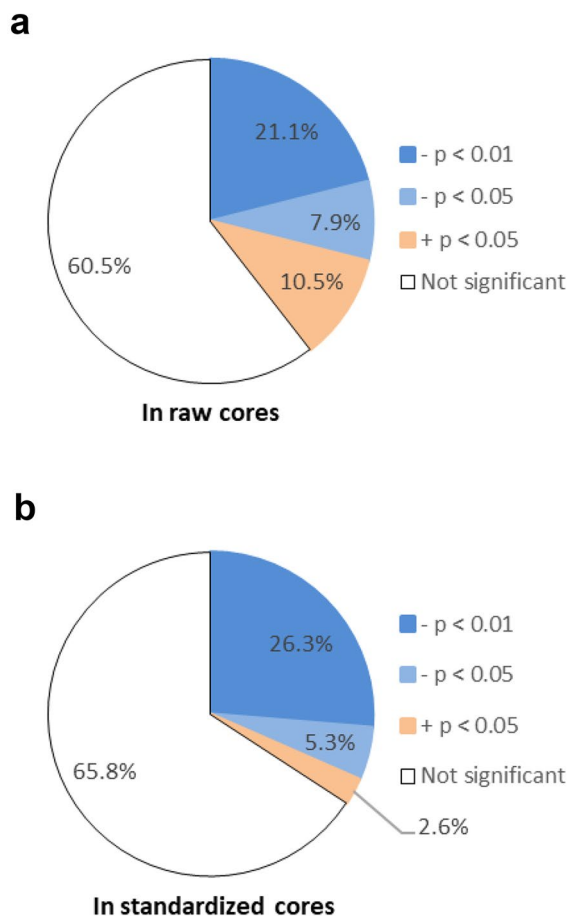
a

In raw cores

b

In standardized cores

Fig. 3 The pie chart shows the percentage of cores with a significant correlation between ring density and width. **a** Shows the percentage of raw data of 38 cores (See Supplementary Materials for the scatter plots for all raw cores). **b** Shows the percentage of standardized data for 38 cores

autumn, and current autumn varied between the ring width and density.

Additionally, the ring weight responses to climate were almost similar to those in our previous report on ring width, besides correlating negatively with the current year's mean temperature from late July to early September and no correlation with the previous year's sunshine duration from mid-August to early September.

Discussions

The relationship among the variations in ring width, density, and weight

Based on the correlation between ring width and density, over 60% of cores did not correlate, despite the raw and standardized series (Fig. 3). This shows that the ring density variation was independent of the individual ring width.

A negative correlation ($p < 0.05$) was observed between the ring width and ring density chronologies (Fig. 5a). Therefore, we considered that the negative correlation between the chronologies of ring width and density was not attributed to the interrelationship of individuals.

From the correlations (Fig. 5) and multiple regression analysis (Table 2) among the chronologies, we discovered that the ring width has the strongest effect on the ring weight; however, the ring density had little effect. These demonstrate that the ring weight variation was controlled mainly by the ring width variation and not the ring density.

Based on the climate response, the ring density responses to summer sunshine duration in the previous year, spring precipitation, summer precipitation, and sunshine duration in the current year differed from the ring width responses (Fig. 6, Shen et al. 2020). These opposite responses between the ring width and ring density correspond to the negative correlations between the chronologies (Fig. 3a). However, a one-month lag in the current summer responses occurred between the ring density and width. Additionally, variations in climate factors that affect either ring density (maximum and mean temperature in the previous summer, precipitation in the previous autumn, and mean and minimum temperature in the current autumn) or ring width (mean and minimum temperature in the previous autumn) were found (Fig. 6). Furthermore, the ring density was independent of the ring width for individuals (Fig. 3). These findings suggested that climatic factors independently affected both the ring width and ring density, respectively.

According to the response of ring width and weight to the climate, the similarity in the climate responses of ring width and ring weight (Fig. 6) corresponded to the positive correlation between the chronologies (Fig. 5b). These results show that climatic factors affect ring weight through ring width changes. The two minor differences in responses, such as the negative correlation with the current year's mean temperature from late July to early September, and the no correlation with the previous year's sunshine duration from mid-August to early September in the ring weight, can be attributed to the varying climate responses between the ring density and the ring width.

However, only a few observations showing the relationship between ring density and ring width in *Betula* species have been recorded. A weak positive or no significant correlation between raw ring width and ring density has been observed in other diffuse-porous species, such as *Fagus sylvatica*, in Europe (Bouriaud et al. 2004; Bontemps et al. 2013; Diaconu et al. 2016) also stated that ring width was strongly related to soil water deficit between May and August; however, the ring density correlated with temperature during the growing season and rainfall in August.

Fig. 4 Residual tree-ring density (**a**) and weight chronologies (**b**). Thick solid lines show the residual chronologies. Shaded areas indicate the number of trees in the chronologies. Thick-dotted lines represent the expressed population signal (EPS) for the residual chronologies (the central value of the 41-year running windows). Thin dotted horizontal lines at EPS = 0.85 represent the reliability threshold presented by Wigley et al. (1984)
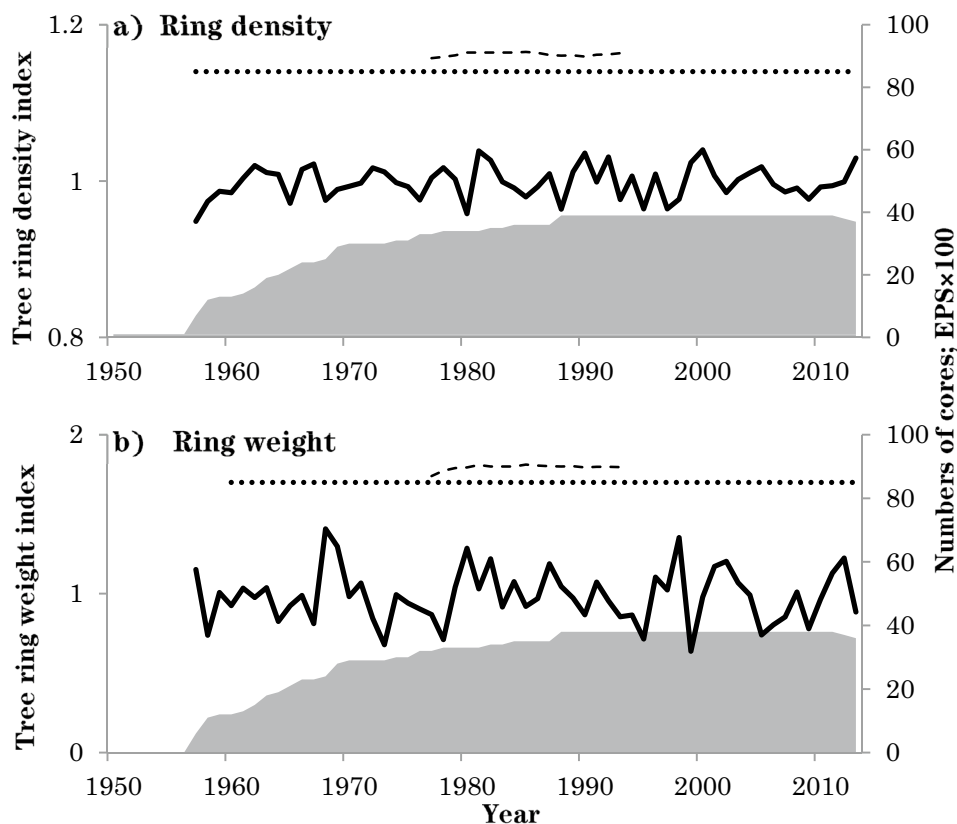

Table 1 Basic statistics for residual chronologies of ring density and weight

	Number of trees (cores) in chronologies	Mean DBH (range)	Mean values (standard deviation)	Period of chronology		Mean correlation between trees	Expressed population signals (EPS)	Signal to noise ratio
Ring density	26 (38)	21.01 cm (15.5–32.0 cm)	0.64 g/cm³ (0.06)	1957	2013	0.23	0.89	7.51
Ring weight			0.10 g/cm² (0.06)	1957	2013	0.23	0.88	8.03

Previous reports and our results showed that ring density variations in these two diffuse-porous species were independent of those in ring width, and the ring width and ring density had independent climatic limiting factors.

Effects of climate factors on ring density

The responses of ring density to the previous year's summer climate show that a higher temperature from mid-July to late August, longer sunshine duration from early August to early September, and less precipitation from mid-August to early October limit the ring density of the following year (Fig. 6). This period is immediately after the rainy season, from mid-June to mid-July, with the highest temperatures

always observed (Fig. 1a). Furthermore, the lowest average soil water content was also observed in August at the neighboring site (Fig. 1b). These findings suggest that the ring density was restricted by dryness from the mid-summer to early autumn of the previous year (Fig. 6).

The precipitation of the current May was negatively correlated with the ring density chronology (Fig. 6). This period was immediately after snowmelt at the site (Noh et al. 2017). Also, the cambial cell division (Shen et al. 2020) and leaf expansion (Nagai et al. 2013) began in mid-May. Therefore, more rainfall at the beginning of cambium division, and leaf expansion negatively affect the ring density.

Sunshine duration, maximum, and mean temperature from mid-June to early August in the current year showed
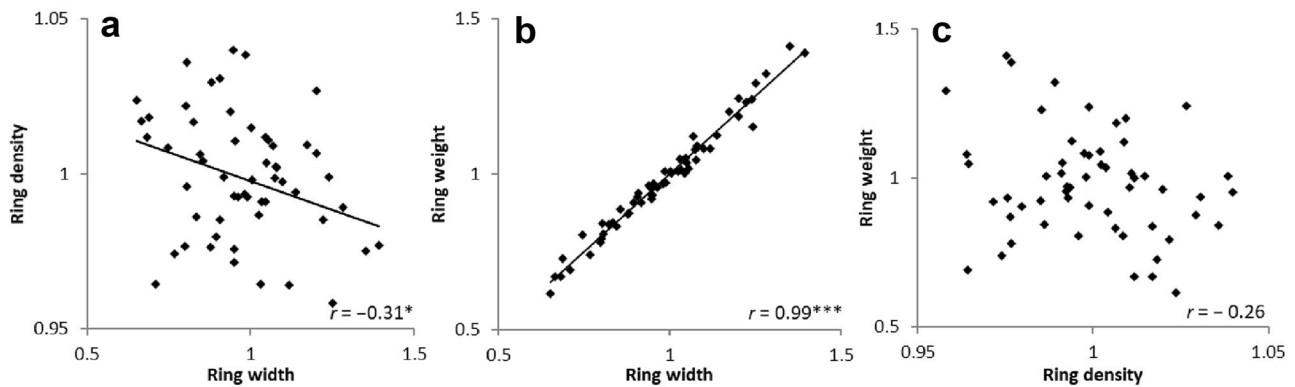
Fig. 5 The scatter plot of chronologies. **a** Ring weight residual chronology variation with ring width residual chronology. **b** Ring weight residual chronology variation with ring density residual chronology. **c** Ring density residual chronology variation with ring width residual chronology. *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$

Table 2 Multiple regression analysis to assess the chronologies of ring width and density impact on ring weight chronology. The interpreted regression coefficient table for ring width and density

	Coefficients	Standard error	t value	p value
Intercept	− 0.501	0.187	− 2.680	0.010
Ring width	1.024	0.021	48.042	<0.001
Ring density	0.478	0.180	2.663	0.010
Adjusted R^2	0.98			
F test	1237.66			
Significant F	<0.001			

a positive correlation with the ring density chronology, whereas precipitation negatively correlated with the ring density chronology (Fig. 6). The period that showed a significant correlation covered the rainy season. In July, the sunshine duration correlated positively with the mean temperature ($r = 0.60$, at $p < 0.01$) and maximum temperature ($r = 0.57$, at $p < 0.01$), respectively, at Takayama. These findings revealed that less precipitation during the current rainy season positively affected the ring density, and the higher temperature or/and longer sunshine duration positively affected ring density. The Photosynthetic Photon Flux Density reduction was observed in another study at the site, under a long active rain front in the summer rainy season (Saigusa et al. 2010). We considered past findings and present results and stated that insufficient sunlight during the rainy season reduced photosynthetic production and consequently controlled the ring density in the current year.

A positive correlation between mean and minimum temperature and ring density chronology was observed in October (Fig. 6), corresponding to the period after the cambium division ended (Shen et al. 2020). This result

indicates that a higher nighttime temperature in October increased ring density.

Effects of climate factors on the ring weight

We found that the ring weight was primarily affected by the ring width. The significant correlation between ring weight and temperature in the previous autumn is related to our previous study, which revealed that high nighttime temperatures extend the period of yellow leaves and/or increase respiration rate, consequently increasing the respiration that consumes photosynthetic products required for the following year's ring width (Shen et al. 2020).

The current summer's higher temperature, long sunshine duration, and less precipitation restricted the ring width, limiting the ring weight. These responses are also due to our previous study, which showed that dry stress reduces or stops cambial cell division during the summer, shortening or reducing the growth rate and decreasing the ring width.

The climate responses of the ring width and weight in the current summer agree with previous research results that revealed that the ring width of *B. ermanii* was positively correlated with precipitation and negatively correlated with the current year's temperature in August at other sites along with the lower altitudinal distribution limit of *B. ermanii* in central Japan (Takahashi et al. 2003). Thus, we conclude that water stress in the current summer should be one of the primary limiting factors for ring width and ring weight at the lower altitudinal distribution limit of *B. ermanii*.

This study used *B. ermanii* ring density and ring weight to evaluate the responses to climatic conditions at Japan's lower altitudinal distribution limit. Results showed that the raw and standardized ring density were independent of
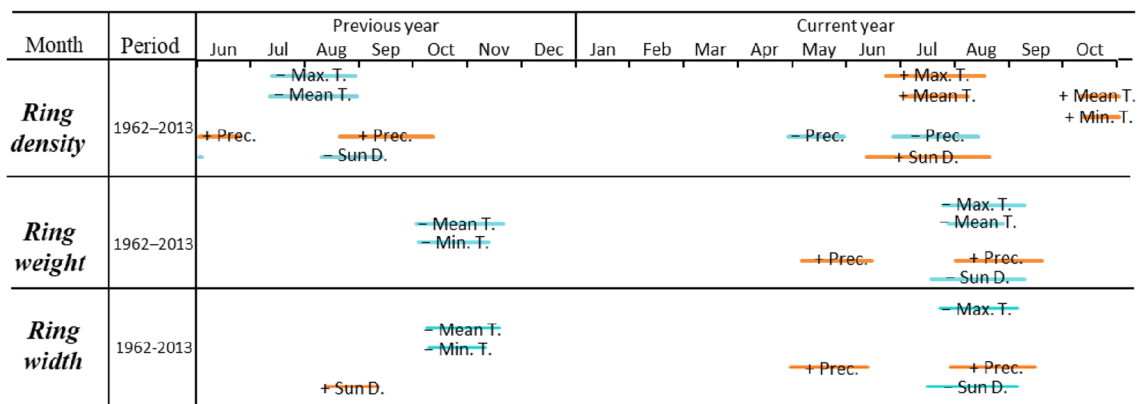
Month	Period	Previous year							Current year									
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Ring density	1962–2013	+ Prec.	− Max. T.; − Mean T.	+ Prec.; − Sun D.	+ Prec.								− Prec.	+ Sun D.	+ Max. T.; + Mean T.; − Prec.; + Sun D.		+ Mean T.	+ Min. T.
Ring weight	1962–2013				− Mean T.; − Min. T.							+ Prec.			− Max. T.; − Mean T.; + Prec.; − Sun D.			
Ring width	1962–2013			+ Sun D.	− Mean T.; − Min. T.							+ Prec.			− Max. T.; + Prec.; − Sun D.			

Fig. 6 Seasonal changes in climate responses at a study site in central Japan. The color bars indicate the period of significant correlation ($p < 0.05$) between residual chronology (Shen et al. 2020 reported the ring width for the individual. Climatic factors independently affected the ring width and ring density. Conversely, the ring width mainly controlled the ring weight, with almost the same climate responses, whereas the ring density did not restrict the ring weight. This study highlights that climate controls ring density and ring weight differently. Therefore, the changes in ring density due to climate have little effect on the carbon fixation. According to the climate responses of ring weight that were limited by the previous autumn's nighttime temperature and the current year's dry climatic conditions, an increase in temperature in summer and autumn reduces the carbon sequestration of the stem of *B. ermanii* growing in their lower distribution limit. Therefore, this study's findings can be used to inform the prediction of the carbon sequestration potential of *B. ermanii*.

Declarations

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