

Growth responses of *Cryptomeria japonica* to drought and frost events in northern Germany

Jonathan M. Kormann¹, Ernst van der Maaten², and Mirko Liesebach^{1*}

¹Thuenen Institute of Forest Genetics, 22926 Großhansdorf, Germany.

*E-mail: m.liesebach@t-online.de

²Chair of Forest Growth and Woody Biomass Production, TU Dresden, 01737 Tharandt, Germany.

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Abstract

Cryptomeria japonica (Thunb. ex L.f.) D.Don is a conifer species native to Japan that has been tested in several European trials, including in Germany, due to its high growth potential. However, its adaptability to emerging climatic conditions and its response to extreme events such as drought and late frost remain poorly understood. Therefore, we studied trees of *C. japonica* originating from the northern part of the natural distribution in Japan and planted at a trial site in northern Germany. Using dendroecological methods, we analysed growth responses to extreme drought and late frost events, assessed variation among trees, and examined growth patterns in response to short- and long-term climate variability. Tree growth was primarily limited by moisture availability in February rather than summer drought, yet individuals showed strong sensitivity to extreme years. Within the analysis period, we identified three extreme drought years and one late frost year. Resistance to late frost was lower than to drought, and relative resilience components differed between spring and summer drought events. Although *C. japonica* achieved high growth rates with diameters up to 58 cm at age 54, its growth in northern Germany was clearly constrained by climatic conditions. Given projected increases in drought and frost extremes, this species may face increased vulnerability under future climate change.

Key words: dendroecology, drought, field trial, frost, Japanese cedar, resilience.

Introduction

The search for suitable and alternative tree species that can withstand prolonged drought periods and altered climatic conditions in the face of climate change is of utmost interest to increase the resilience of native forest ecosystems. Besides native tree species, the focus shifted to

non-native tree species that proved their ecological and economic suitability for cultivation. There are many systematic trials available, investigating growth and tolerance against biotic or abiotic extreme events (Pötzelsberger et al. 2020). Especially, the tolerance to extreme drought events is gaining importance, since such events are suggested to increase rapidly

in the future (IPCC 2021). The introduction of non-native tree species to Germany that might be better adapted to those changing climatic conditions has a long history and comprises species from North America, Europe and Asia (Schober and Spellmann 2001). However, trial experiments with some of these fast-growing species demonstrated unsuitability for forestry purposes. Whereas the number of trials in Germany investigating their growth or climate response is low.

One species that has received little attention in German forestry strategies is *Cryptomeria japonica* (Thunb. ex L.f.) D.Don (Japanese cedar or Japanese redwood; 'sugi' in Japanese). It is native to Japan and thrives in cool- to warm-temperate regions with high humidity and high annual precipitation (Stratmann 1988, Matsumoto et al. 2006). The species is a monotypic genus of conifers. Due to its high economic importance in Japan (4.5 million ha or 45 % of the forested area) and long tradition in commercial forestry since the 17th century, the natural distribution cannot be exactly retraced (Hogrebe 1974, Matsumoto et al. 2006). The use of *C. japonica* has a long history and dates back more than 3,000 years (Takahashi et al. 2023). The discontinuous natural distribution ranges from the southern island Yakushima to the northern part of Honshu, the main island of Japan (Kurata 1964). It was later introduced to Hokkaido at the northern edge of the Japanese archipelago (Eguchi et al. 1965). The species is characterised by high growth rates and can reach heights of up to 50 m (Schober 1977, 1978) and mean diameters at breast height (DBH) of 2 m (Schenck 1939). In Japan, it is one of the most widely used timber species (Dallimore and Jackson 1923). It provides high-quality wood with good workability

and a wide range of uses, such as construction, furniture, and rice wine barrels (Schenck 1939, Hogrebe 1974). In its natural habitat, the species generally lives for 200 to 300 years (Stratmann 1988). In southern Japan, trees up to about 2,000 years old have been recorded on Yakushima Island (Stratmann 1988). *C. japonica* can be susceptible to wind, frost, and snow damage depending on site conditions and provenance (Schenck 1939, Eguchi et al. 1965). Based on its high water demand and limited ability of water uptake, the species is suggested to be susceptible to water stress, especially in regions with limited water availability and dry climates (Schober 1978, Matsumoto et al. 2006, Tange et al. 2009). This susceptibility may be further exacerbated by climate change, as growth declines in *C. japonica* forests in Japan could be linked to water stress and increasing temperatures (Matsumoto et al. 2006). However, a previous dendroecological study in western Germany revealed low resistance of *C. japonica* in extreme drought years, but at the same time, also significantly higher resilience compared with other introduced species (Hoffmann 2019), which can be explained by its isohydric behaviour (Kumagai et al. 2008).

In Europe and especially in Germany, previous *C. japonica* trials have been largely disappointing, which may be explained by using reproductive material of unknown origin, unsuitable climatic conditions and consequently maladaptation to frost and snow damage (Hogrebe 1974, Stratmann 1988). The observed high susceptibility to frost resulted in the recommendations to plant the species under canopy cover in respective regions (Schenck 1939, Hogrebe 1974). On the other hand, this species showed strong sensitivity to crown cover and lateral com-

petition, highlighting the necessity of early silvicultural treatments (Stratmann 1988). However, individual trials reported high growth rates under moist climatic conditions comparable to high-yielding Norway spruce or Douglas fir (Schober 1978, Schober and Spellmann 2001). Especially, trees originating from Akita Prefecture located in the North of Honshu showed the most promising growth responses in Germany (Schenck 1939, Schober and Spellmann 2001). Furthermore, *C. japonica* trees in parks or arboreta have reached impressive sizes (Schenck 1939). Nevertheless, the species has not become widely used in ornamental horticulture due to the brown-purple winter discoloration of individual branches (Schütt et al. 1984).

The mainly disappointing trial experiences in Germany and the observed high susceptibility to frost and drought have led to a general lack of interest in this species in a forestry context. However, since trials for this species are scarce, continuous evaluation of this species under changing climate conditions is necessary for understanding its performance. Therefore, we investigated individuals of the species originating from the northern distribution area, which were planted at a trial site in northern Germany. Using a dendroecological approach, we examined the long-term growth response to climatic fluctuations and investigated the tolerance to extreme drought periods as well as to a late frost event, as a main criterion for the suitability of *C. japonica* in Germany under changing climate conditions. In that way, we quantified the similarity in the growth response of individual trees in order to evaluate intraspecific adaptation to extreme events.

The aim of this study is to assess the suitability of *C. japonica* for future forestry use in Central Europe by evaluating its growth response, tolerance to climatic ex-

tremes, and variation in resilience.

Material and Methods

Study site

We investigated the growth response of six trees of *C. japonica* using a small trial (0.13 ha) located in the north-east of Hamburg (53°31'8.76" N, 10°15'52.49" E). The trial site is characterised by moist conditions with an annual precipitation of 802 mm and a mean annual temperature of 9.3 °C (Fig. 1). The trial was established in 1972 with six-year-old trees of a single provenance. The spacing is 6 × 4 m with no replication. The mother trees were selected in the Matsumae district in the south of Hokkaido, Japan. Here, *C. japonica* trees were introduced from the Akita prefecture and grew near the northern ecological limit of the species' natural distribution (Matsumoto et al. 2006). The offspring were selected according to their frost hardiness and survived -17 °C of midwinter temperature (Eguchi et al. 1965). One-year-old plants were brought to the institute in Großhansdorf as part of a research collaboration. Here, they were cultivated in the institute's tree nursery. In 1972, the field trial was established with 52 trees in total. Today, 37 trees exist at the trial site.

Sampling and measurements

For assessing the growth of the trees, DBH was measured in 1980 (age 14) and 2020 (age 54) on the living trees. To evaluate the total growth performance of the living trees, we focused on the DBH at age 54 (37 trees in total). For the examination of the growth response, we selected randomly six trees, four trees are

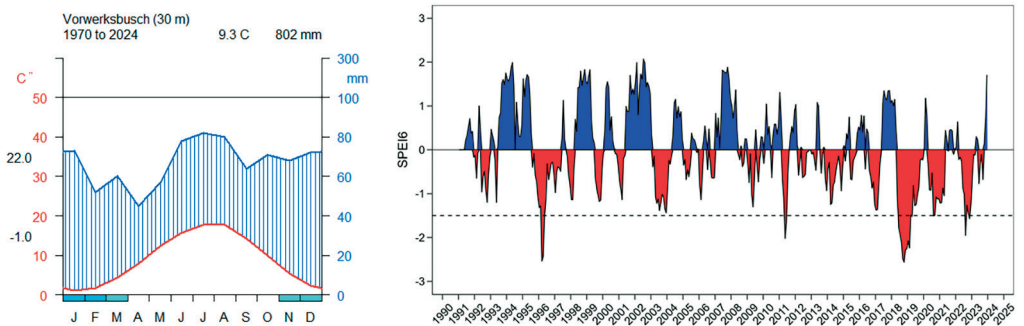


Fig. 1. Walther-Lieth diagram (left) for the period 1970–2024 and the Standardised Precipitation Evapotranspiration Index (right) for the period from 1991 to 2024 at the trial site Vorwerksbusch.

Note: The dashed line marks the -1.5 threshold used to identify drought years.

clones (35_11, 378_160, 409_195, and 421_217) and two trees are seedlings (268 and 284). In winter 2024, increment cores on the six trees were sampled in one direction at 1.3 m, to investigate the growth responses to past climate fluctuations and extreme drought events. The increment cores were air-dried and prepared in the laboratory using a WSL microtome (Gärtner and Nievergelt 2010) and digitised using the ATRICS-system (Levanič 2007). On these high-resolution images, annual ring-width measurements were conducted and statistically cross-dated using CooRecorder and CDendro (version 9.6.3, Cybis Elektronik & Data AB, Sweden). Ring-width series were detrended using a cubic smoothing spline function with a 50 % frequency cut-off at 30 years to obtain high-frequency climatic signals (Speer 2011). Chronology statistics were calculated to assess and validate the individual ring-width series using the R package dplR (Bunn 2008). More specifically, we calculated the expressed population signal (EPS) to validate the adequacy of the subsamples in representing the theoretical population, as well as the Gleichläufigkeit (GLK) to

assess the similarity in growth response. Furthermore, we calculated the Gini coefficient to characterise the dissimilarity of ring width over time (Bunn et al. 2013).

Climate data

For the investigation of the growth response to long- and short-term climatic fluctuations, we used monthly means of temperature, precipitation and evapotranspiration (available from 1991) data from a 1×1 km gridded database available at the German Weather Service (DWD Climate Data Center 2022a,b, 2024). Furthermore, we identified the three driest years, 1996, 2003 and 2018, within the period from 1991 to 2023 by calculating the Standardised Precipitation Evapotranspiration Index (SPEI) based on monthly precipitation and evapotranspiration using the R package SPEI (Beguería and Vicente-Serrano 2023). Therefore, we used a timescale of 6 months to account for the water availability for tree growth (SPEI6). Drought years were confirmed when SPEI values exceeded a threshold of -1.5 during the vegetation period (April to September), following a classification

after McKee et al. (1993) (Fig. 1). In addition, we identified a late frost event in 2010 and considered this year as an extreme year in the analysis as well.

The evaluation of climate sensitivity to long-term climatic fluctuations was done using climate-growth relationships. Therefore, bootstrapped correlations were calculated between the individual detrended chronologies and monthly temperature, precipitation, and SPEI6. To consider the influence of the previous year conditions, these correlations were calculated over a 16-month window from previous June to current-year September. The calculations considered the period from 1992 to 2023, in which values for the evapotranspiration were available (necessary for the calculation of SPEI values), using the R package treeclim (Zang and Biondi 2022).

In addition to assessing the long-term growth response to climate impacts, we quantified the individual trees' response in the identified extreme years using different resilience components provided by Lloret et al. (2011). Specifically, resistance was calculated as the ratio between ring width during and before a drought year ($Dr/PreDr$), taking into account the growth depression during the extreme event. The ability of a tree to reach the growth level before the drought event is defined as resilience and is calculated as the ratio between the growth after and before the extreme event ($PostDr/PreDr$). Furthermore, resilience can be weighted by the damage experienced during the extreme events ($(PostDr - Dr)/PreDr$) and is called relative resilience, defining the speed of the recovery of a tree while taking into account the damage experienced during the extreme event. For the calculation of the resilience components, we considered three years before and after an extreme event, using the R package pointRes (van

der Maaten-Theunissen et al. 2015). To consider differences in the stability of the growth responses among the identified extreme years, which may differ in timing, duration, or severity, an ANOVA was performed with the resilience components as response variables and the extreme years as fixed effects. Significant differences between extreme years were calculated using a post-hoc test and displayed via compact letter display. The data analysis was performed in the R programming environment (R Core Team 2023).

Results

Growth and annual increment

DBH at age 54 (in 2020) of *C. japonica* trees on the trial site varied between 34.6 and 58.8 cm. Mean height at the age of 54 was 26.0 m.

The individual chronologies show a strong common signal, as indicated by a high mean interseries correlation ($\bar{r} = 0.718$) and high Gleichläufigkeit ($GLK = 0.71$). The EPS of 0.938 exceeded the common prescribed threshold of 0.85, underlining the common signal of the individual chronologies (Wigley et al. 1984). The standard deviation was similar among trees (Table 1), except for tree 409_195. This tree shows the highest variation in the common overlap period from 1989 to 2024 (Fig. 2), indicated by the highest standard deviation and the highest Gini coefficient. The mean of the chronologies was similar among trees, with tree 421_217 showing the lowest value (Table 1). In contrast, the first-order autocorrelation varies between individuals with the highest autocorrelation for 35_11. Furthermore, the variation in ring width decreases towards the higher ages. Thereby, some years, such as 2003

Table 1. Chronology statistics for the six analysed trees.

Tree number	DBH, cm	Mean, mm	StDev, mm	Gini	AR1
268	54.9	4.274	1.880	0.244	0.529
284	46.0	4.020	1.840	0.236	0.426
35_11	47.8	4.467	1.708	0.214	0.703
378_160	50.3	4.967	2.408	0.257	0.454
409_195	44.3	4.961	3.657	0.395	0.463
421_217	53.4	3.720	1.804	0.264	0.606

Note: DBH was measured at age 54 (in 2020). Mean – mean ring width, StDev – standard deviation, Gini – Gini coefficient, AR1 – first-order autocorrelation.

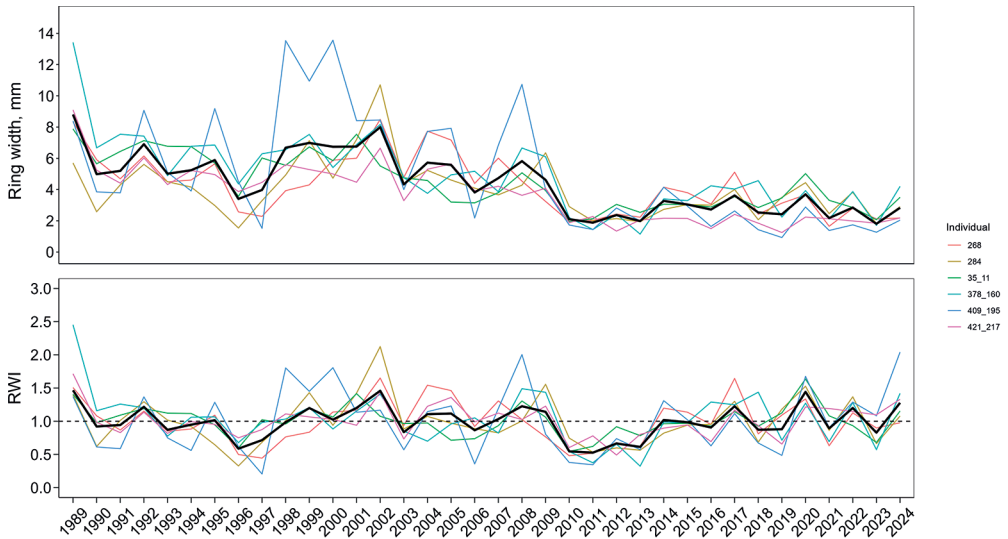


Fig. 2. Ring width and ring-width index (RWI) for the common overlap period from 1989 to 2024.

Note: colours represent different trees; the black line indicates the mean.

and 2010, showed a synchronous growth depression in RWI across all chronologies (Fig. 2).

Main climatic drivers of growth

In accordance with the common growth response, the climate-growth relationships revealed similar sensitivity to the climate variables (Fig. 3). For example, all trees showed a positive correlation

with temperature in February, and at least three of six trees also correlated with temperatures in January and March. Also, trees showed high sensitivity to precipitation in February. In contrast, summer drought did not appear to be a major climatic driver as indicated by the overall weak correlations with SPEI6 and precipitation in June and July. Overall, previous-year conditions had no significant impact on growth.

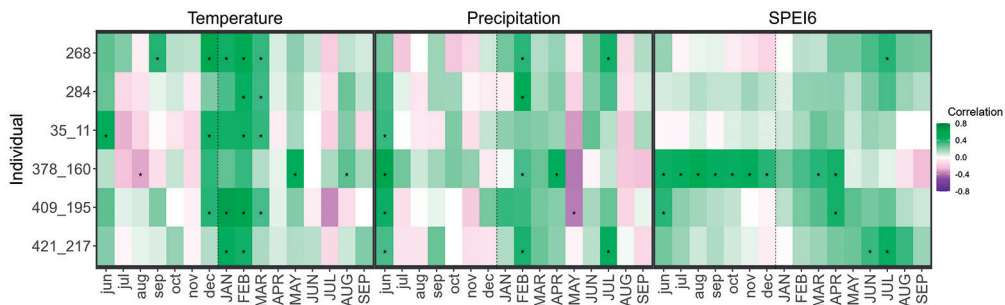


Fig. 3. Heatmap of bootstrapped correlations between tree-ring width and monthly temperature, precipitation, and SPEI6.

Note: Correlations were calculated over a 16-month window from previous-year June (jun) to current-year September (SEP) for the period 1993 to 2023. Colours indicate correlation strength, asterisks significant correlations.

Response to extreme conditions

Within the period from 1991 to 2023, we identified 1996, 2003 and 2018 as the driest years based on SPEI6 values during the vegetation period, whereas 2010 was characterised by a late frost event in May and low winter temperatures (Table 2). The drought years differed in severity and timing. While in 1996 a spring drought was observed, 2003 and 2018 were marked by summer drought, as indicated by the SPEI6 values (Table 2).

Resistance to drought was similar

between the extreme years, whereas resistance to late frost was lower (Fig. 4), indicating no clear difference in resistance between summer and spring droughts. The highest variation was found in 2018 and the lowest in 2010. In contrast, relative resilience during the spring drought in 1996 differed significantly from the summer drought of 2003 and 2018, as well as the late frost conditions in 2010. For 2010, relative resilience was lowest, showing that the trees did not return to pre-disturbance growth level within the 3 years (see also Fig. 2). The ability to reach pre-dis-

Table 2. Extreme years characterised by minimum SPEI6 values for the vegetation period (Apr–Sep) and corresponding mean SPEI6 values for the vegetation period, spring (Apr–May) and summer (Jun–Aug), including May temperature data for the late frost event in 2010.

Extreme year	SPEI6				Frost	
	Minimum (Apr–Sep)	Mean (Apr–Sep)	Mean (Apr–May)	Mean (Jun–Aug)	Minimum May T, °C	Mean May T, °C
1996	-2.43 (Apr)	-1.09	-2.15	-0.71	-	-
2003	-1.38 (Jul)	-1.17	-0.81	-1.24	-	-
2010	-	-	-	-	5.7	7.6
2018	-3.25 (Jul)	-1.71	0.17	-2.38	-	-

Note: Drought years differed in severity and timing, with 1996 experiencing a spring drought, whereas 2003 and 2018 were marked by summer drought, as reflected by the SPEI6 values. For 2010, the minimum monthly temperature in May (Minimum May T, °C) and the mean minimum May temperature for the period 1990–2023 (Mean May T, °C) are shown.

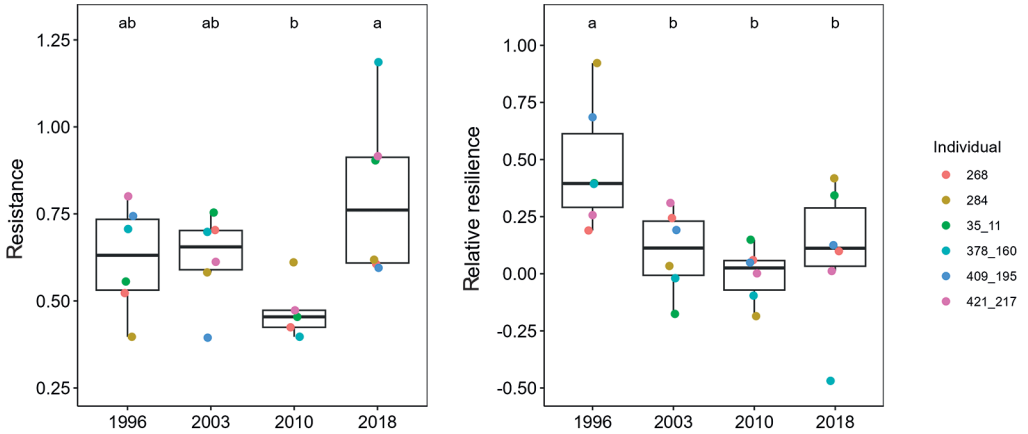


Fig. 4. Resistance (left) and relative resilience components (right) for the identified extreme drought years (1996, 2003, and 2018) and the late frost year (2010).

Note: Colours refer to the trees ($n = 6$). Different letters indicate statistically significant differences between extreme years; means sharing the same letter are not significantly different.

turbance growth levels was highest for 1996, also showing the greatest variation among trees.

Discussion

Due to its high growth potential in its natural range, *C. japonica* became the focus of various trial experiments across Europe during late 19th and 20th centuries, with early tests in the UK, Sweden, Denmark, and Germany mostly showing unsatisfactory results (Schenck 1939, Thiringer 1967, Högberg 1974). One reason may be the uncontrolled use of different provenances from the natural distribution, since it varies strongly in climatic conditions (annual precipitation, temperature, and the amount of snowfall), leading to genetic and morphological differences between populations caused by natural selection (Kimura et al. 2014, Tsumura et al. 2014). However, later trials in Germany documented provenances and reported high growth rates of northern provenances

comparable to the first and second yield classes of Japanese yield tables (Schober 1978, Schober and Spellmann 2001). Compared to the native fast-growing Norway spruce, *C. japonica* exceeded by far the first yield class, with the best growing trees originating from the Akita Prefecture in northern Honshu (Schober and Spellmann 2001). The trees investigated in this study showed a wide range in growth (DBH: 34.6–58.8 cm), which is also higher compared to the first yield class of Norway spruce at age 55 (DBH: 38.6 cm; Albert et al. 2021). As these trees also originate from the northern parts of the natural distribution, previous observations of high growth rates compared to native species are confirmed.

In contrast to the partly impressive sizes of *C. japonica* in Germany, its response to climatic fluctuations may represent a limiting factor in the introduced range, potentially contributing to unsatisfactory results and limited silvicultural interest. Climatic conditions in Japan differ substantially from those in Germany. The

average annual precipitation is more than twice as high, reaching up to 4,000 mm in the southern areas (Thiringer 1967). As a result, the species is adapted to humid and mild climates, whereas growth may become constrained under drier conditions (Hoffmann 2019). In the climate–growth correlation analysis (Fig. 3), summer drought was identified as a significant growth-limiting factor in only two trees, suggesting that it is not the dominant climatic driver. Instead, moisture conditions in February (temperature and precipitation) showed a stronger correlations with tree growth, consistent with findings for native conifers such as pine (Stolz et al. 2021). Elevated spring temperatures may promote photosynthesis once specific thermal thresholds are reached (Harvey et al. 2020). Nevertheless, the event-based analysis (Fig. 4) indicates measurable growth reductions during drought years, reflecting a detectable drought sensitivity. Such growth responses are consistent with isohydric behaviour, characterised by early stomatal closure under water deficit to limit transpiration (McDowell et al. 2008), as previously reported for *C. japonica* (Kumagai et al. 2008, Tange et al. 2009, Hoffmann 2019). Importantly, relative resilience differed between spring and summer drought events, with faster recovery following spring drought. This suggests that seasonal timing influences post-drought growth dynamics and highlights that resistance during drought and resilience after drought represent distinct aspects of the growth response.

Interestingly, the lowest resistance was observed in the year with a late frost event, showing also the lowest variation among the trees studied (Fig. 4). According to Eguchi et al. (1965), the trees are progenies of trees growing in the Matsu-mae District, where they experienced tem-

peratures between -17 and -5 °C. For the selection of the frost-hardest *C. japonica*, different types were determined based on crown architecture, bark and form of needles and observed in terms of desiccation as well as resistance to frost damage (Eguchi et al. 1965). It therefore seems surprising that resistance to late frost was lower than in the drought years. However, low frost resistance is a commonly observed pattern in previously described trials in Germany (Schober 1978, Schober and Spellmann 2001). Additionally, the species showed a high susceptibility to snow damage (Schober and Spellmann 2001), which could not be investigated in this study (missing data). Furthermore, the small number of trees examined limits the comparability with previous studies. However, the results clearly underline current observations and recommendations that this species is conditionally suitable for cultivation under mild and humid climatic conditions (Hogrebe 1974, Schober and Spellmann 2001, Hoffmann 2019).

In order to elucidate the biological mechanisms of how *C. japonica* responds to different environmental conditions, Nose et al. (2023) analysed the annual transcriptome dynamics of a *C. japonica* clone planted at three climatically different locations using microarrays. Takashima et al. (2021) established a high-throughput method for evaluating clonal stress responses to drought stress using infrared thermography and chlorophyll fluorescence methods in *C. japonica*. The method is intended to enable the evaluation of clonal stress responses in the species in order to enhance the breeding program for drought tolerance.

The geographical latitude and the associated period of sunshine (duration of sunlight) have an influence on the adaptability of tree species, particularly in the

northern latitudes of Europe (e.g., *Picea abies*, Schmidt-Vogt 1986). This has not been confirmed in the introduction of Japanese tree species such as *Larix kaempferi* (Schober and Rau 1991), *Betula maximowicziana* (Liesebach et al. 1997), and *Betula platyphylla* var. *japonica* (Liesebach et al. 2007) to Germany.

Conclusions

Cryptomeria japonica has been described as highly susceptible to water stress both in Japan (Matsumoto et al. 2006) and in Germany (Schenck 1939, Schober 1978) in the context of climate change with increasingly frequent drought periods. The cultivation of *C. japonica* should therefore proceed with caution (e.g. Stratmann 1988). Nevertheless, high growth rates under favourable, mild conditions and the use of appropriate provenances suggest that good productivity is possible. The long-standing recommendation to plant the species under canopy to reduce frost damage should be followed (Hogrebe 1974), especially when growing provenances from the southern part of the natural distribution, which are more sensitive to frost (Schober and Spellmann 2001). A comparison of provenances was not possible in this study and remains an important topic for further research. It also remains unclear whether the species can adapt to the rapidly changing climatic conditions in the introduced range, despite its broad ecological amplitude and adaptability within its natural distribution. Overall, the good growth performance and the observed tolerance to drought and late frost – even under relatively poor site conditions – indicate that *C. japonica* should not be neglected in discussions on future tree species selection under climate change.

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References

- ALBERT M., NAGEL J., SCHMIDT M., NAGEL R.V., SPELLMANN H. 2021. Eine neue Generation von Ertragstafeln für Eiche, Buche, Fichte, Douglasie und Kiefer [Datensatz]. Zenodo. <https://doi.org/https://doi.org/10.5281/zenodo.6343906>
- BEGUERÍA S., VICENTE-SERRANO S.M. 2023. SPEI: Calculation of the Standardized Precipitation-Evapotranspiration Index. <https://cran.r-project.org/package=SPEI>
- BUNN A.G. 2008. A dendrochronology program library in R (dplR). *Dendrochronologia* 26(2): 115–124. <https://doi.org/10.1016/j.dendro.2008.01.002>
- BUNN A.G., JANSMA E., KORPELA M., WESTFALL R.D., BALDWIN J. 2013. Using simulations and data to evaluate mean sensitivity (ζ) as a useful statistic in dendrochronology. *Dendrochronologia* 31(3): 250–254. <https://doi.org/10.1016/j.dendro.2013.01.004>
- DALLIMORE W., JACKSON B. 1923. A Handbook of Conifera. Edward Arnold & CO: 252–258.
- DWD CLIMATE DATA CENTER 2022a. Grids of monthly averaged daily minimum air temperature (2m) over Germany. Version v1.0. Available at: www.dwd.de
- DWD CLIMATE DATA CENTER 2022b. Grids of monthly total precipitation over Germany. Version v1.0. Available at: www.dwd.de
- DWD CLIMATE DATA CENTER 2024. Monthly grids of the accumulated potential evapotranspiration over Germany. Version v1.0. Available at: www.dwd.de

- transpiration over grass. Available at: www.dwd.de
- EGUCHI T., SAKAI A., USUI G., UEHARA T. 1965. Studies of Selection of Frost-Hardy *Cryptomeria* I. *Silva Genetica* 15(3): 84–89.
- GÄRTNER H., NIEVERGELT D. 2010. The core-microtome: A new tool for surface preparation on cores and time series analysis of varying cell parameters. *Dendrochronologia* 28(2): 85–92. <https://doi.org/https://doi.org/10.1016/j.dendro.2009.09.002>
- HARVEY J.E., SMILJANIĆ M., SCHARNWEBER T., BURAS A., CEDRO A., CRUZ-GARCÍA R., DROBYSHEV I., JANECKA K., JANSONS Ā., KACZKA R., KLISZ M., LÄÄNELAID A., MATISONS R., MUFFLER L., SOHAR K., SPYT B., STOLZ J., VAN DER MAATEN E., VAN DER MAATEN-THEUNISSEN M., WILMKING M. 2020. Tree growth influenced by warming winter climate and summer moisture availability in northern temperate forests. *Global Change Biology* 26(4): 2505–2518. <https://doi.org/10.1111/gcb.14966>
- HOFFMANN N. 2019. Zuwachspotenziale und Klimasensitivität eingeführter Baumarten in Nordrhein-Westfalen. Georg-August-Universität Göttingen. 265 p.
- HOGREBE H. 1974. Ist *Cryptomeria japonica* in Mitteleuropa anbauwürdig? Mitteilungen der Deutschen Dendrologischen Gesellschaft 67: 73–83.
- IPCC 2021. Summary for Policymakers. In: Masson-Delmotte V., Zhai P., Pirani A., Connors S.L., Péan C., Berger S., Caud N., Chen Y., Goldfarb L., Gomis M.I., Huang M., Leitzell K., Lonnoy E., Matthews J.B.R., Maycock T.K., Waterfield T., Yelekçi O., Yu R., Zhou B. (Eds), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>
- KIMURA M.K., UCHIYAMA K., NAKAO K., MORIGUCHI Y., JOSE-MALDIA L.S. 2014. Evidence for cryptic northern refugia in the last glacial period in *Cryptomeria japonica*. *Annals of Botany* 114(8): 1687–1700. <https://doi.org/10.1093/aob/mcu197>
- KUMAGAI T., TATEISHI M., SHIMIZU T., OTSUKI K. 2008. Transpiration and canopy conductance at two slope positions in a Japanese cedar forest watershed. *Agricultural and Forest Meteorology* 148(10): 1444–1455. <https://doi.org/10.1016/j.agrformet.2008.04.010>
- KURATA S. 1964. Illustrated important forest trees of Japan (1st edition). Chikyu Shuppan. 217 p.
- LEVANIČ T.O.M. 2007. Research report AT-RICS – A new system for image acquisition in dendrochronology. *Tree-Ring Research* 63(2): 117–122. <https://doi.org/10.3959/1536-1098-63.2.117>
- LIESEBACH M., STEPHAN B.R., SCHWAB E. 1997. Wuchs- und Ertragsleistung von *Betula maximowicziana* Regel. *Allg. Forst- und Jagdzeitung*. Frankfurt am Main 168(8): 141–149.
- LIESEBACH M., STEPHAN B.R., SCHWAB E., KRAUSE H.A. 2007. Wuchs- und Ertragsleistung von *Betula platyphylla* var. *japonica* (Miq.) Hara auf norddeutschen Standorten. *Archiv für Forstwesen und Landschaftsökologie*, Deutscher Landwirtschaftsverlag, Berlin 41(1): 15–25. https://www.library.sk/ar/sldk/sk/detail-sldk_un_cat-0018039-Wuchs-und-Ertragsleistung-von-Herkunften-der-Betula-platyphylla-Sukaczew-var-japonica-Miq-Hara/?utm_source=chatgpt.com
- LLORET F., KEELING E.G., SALA A. 2011. Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. *Oikos* 120(12): 1909–1920. <https://doi.org/10.1111/j.1600-0706.2011.19372.x>
- MA Q., HUANG J.G., HÄNNINEN H., BERNINGER F. 2019. Divergent trends in the risk of spring frost damage to trees in Europe with recent warming. *Global Change Biology* 25(1): 351–360. <https://doi.org/10.1111/gcb.14479>
- MATSUMOTO Y., SHIGENAGA H., MIURA S., NAGAKURA J., TAODA H. 2006. Mapping of Japanese Cedar (*Cryptomeria japonica*) Forests Vulnerable to Global Warming in Japan. *Global Environmental Change* 10: 181–188.

- McDOWELL N., POCKMAN W.T., ALLEN C.D., DAVID D., COBB N., KOLB T., PLAUT J., SPERRY J., WEST A., WILLIAMS D.G., YEPEZ E.A. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist* 178(4): 719–739. <https://doi.org/10.1111/j.1469-8137.2008.02436.x>
- McKEE T.B., DOESKEN N.J., KLEIST J. 1993. The relationship of drought frequency and duration to time scales. In: Eighth Conference on Applied Climatology. American Meteorological Society, 17–22 January 1993, Anaheim, California. 8 p.
- NOSE M., HANAOKA S., FUKATSU E., KURITA M., MIURA M., HIRAOKA Y., IKI T., CHIGIRA O., MISHIMA K., TAKAHASHI M., WATANABE A. 2023. Changes in annual transcriptome dynamics of a clone of Japanese cedar (*Cryptomeria japonica* D. Don) planted under different climate conditions. *PLoS ONE* 18(2), e0277797. <https://doi.org/10.1371/journal.pone.0277797>
- PÖTZELSBERGER E., SPIECKER H., NEOPHYTOU C., MOHREN F., GAZDA A., HASENAUER H. 2020. Growing Non-native Trees in European Forests Brings Benefits and Opportunities but Also Has Its Risks and Limits. *Current Forestry Reports* 6(4): 339–353. <https://doi.org/10.1007/s40725-020-00129-0>
- R CORE TEAM 2023. A Language and Environment for Statistical Computing (4.3.1). R Foundation for Statistical Computing. <https://www.r-project.org/>
- SCHENCK C.A. 1939. *Fremdländische Wald- und Parkbäume*, II. Band. Paul Parey: 144–151.
- SCHMIDT-VOGT H. 1986. Die Fichte. Band II/1. Paul Parey: 208–249.
- SCHOBER R. 1977. Erste Ergebnisse von Anbauversuchen mit Tannen und anderen Koniferen aus Japan im Vergleich mit nordamerikanischen und europäischen Nadelhölzern. *Allgemeine Forst Und Jagdzeitung* 148(10/11): 197–207.
- SCHOBER R. 1978. Erste Ergebnisse von Anbauversuchen mit Tannen und anderen Koniferen aus Japan im Vergleich mit nordamerikanischen und europäischen Nadelhölzern (Teil II). *Allgemeine Forst Und Jagdzeitung* 149(11/12): 197–223.
- SCHOBER R., RAU H.M. 1991. Ergebnisse des I. Internationalen Japanlärchen-Provenienzversuches. *Schriften aus der forstlichen Fakultät Göttingen* (102). J.D. Sauerländer's Verlag. 168 p.
- SCHOBER R., SPELLMANN H. 2001. Von Anbauversuchen mit Tannen und anderen Koniferen aus Japan, Nordamerika und Europa. *Schriften aus der forstlichen Fakultät Göttingen* (130). J.D. Sauerländer's Verlag. 178 p.
- SCHÜTT P., LANG K., SCHUCK H. 1984. *Nadelhölzer in Mitteleuropa*. Gustav Fischer Verlag. Stuttgart, New York. 274 p.
- SPEER J.H. 2011. *Fundamentals of tree-ring research*. University of Arizona Press. xvi–333 p.
- STOLZ J., VAN DER MAATEN E., KALANKE H., MARTIN J., WILMKING M., VAN DER MAATEN-THEUNISSEN M. 2021. Increasing climate sensitivity of beech and pine is not mediated by adaptation and soil characteristics along a precipitation gradient in northeastern Germany. *Dendrochronologia* 67, 125834. <https://doi.org/10.1016/j.dendro.2021.125834>
- STRATMANN J. 1988. Ausländeranbau in Niedersachsen und den angrenzenden Gebieten. Inventur und waldbaulich-ertragskundliche Untersuchungen. In: *Schriften aus der forstlichen Fakultät Göttingen* (91). Sauerländer's Verlag. 131 p.
- TAKASHIMA Y., HIRAOKA Y., MATSUSHITA M., TAKAHASHI M. 2021. Evaluation of Responsivity to Drought Stress Using Infra-red Thermography and Chlorophyll Fluorescence in Potted Clones of *Cryptomeria japonica*. *Forests* 12(1), 55. <https://doi.org/10.3390/f12010055>
- TAKAHASHI M., MIURA M., FUKATSU E., HIRAOKA Y., KURITA M. 2023. Research and project activities for breeding of *Cryptomeria japonica* D. Don in Japan. *Journal of Forest Research* 28(2): 83–97. <https://doi.org/10.1080/13416979.2023.2172794>
- TANGE T., YANAGA K., OSAWA H., MASUMORI M. 2009. Effects of evening and nighttime

leaf wetting on stomatal behavior of *Cryptomeria japonica* growing in dry soil. *Photosynthetica* 47(2): 313–316. https://ps.ueb.cas.cz/artkey/phs-200902-0021_effects-of-evening-and-nighttime-leaf-wetting-on-stomatal-behavior-of-cryptomeria-japonica-growing-in-dry-soil.php

THIRINGER J. 1967. Über die Kultur der *Cryptomeria japonica* (L.f.) D. DON in Europa. *Mitteilungen der Deutschen Dendrologischen Gesellschaft* 63: 62–85.

TSUMURA Y., UCHIYAMA K., MORIGUCHI Y., KIMURA M.K., UENO S., UJINO-IHARA T. 2014. Genetic differentiation and evolutionary adaptation in *Cryptomeria japonica*. *G3: Genes, Genomes, Genetics* 4(12): 2389–2402. <https://doi.org/10.1534/>

g3.114.013896

VAN DER MAATEN-THEUNISSEN M., VAN DER MAATEN E., BOURIAUD O. 2015. PointRes: An R package to analyze pointer years and components of resilience. *Dendrochronologia* 35: 34–38. <https://doi.org/10.1016/j.dendro.2015.05.006>

WIGLEY T.M.L., BRIFFA K.R., JONES P.D. 1984. On the Average Value of Correlated Time Series, with Applications in Dendroclimatology and Hydrometeorology. *American Meteorological Society* 23: 201–213. [https://doi.org/10.1175/1520-0450\(1984\)023%3C0201:OTAVOC%3E2.0.CO;2](https://doi.org/10.1175/1520-0450(1984)023%3C0201:OTAVOC%3E2.0.CO;2)

ZANG C., BIONDI F. 2022. R Package 'tree-clim' (2.0.6.0). <https://doi.org/10.1111/ecog.01335>