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Impact of heatwave and thinning on tree growth and soil water content in young lodgepole pine forests

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ABSTRACT

Extreme climate events (e.g., heatwaves and droughts) are becoming increasingly frequent due to global climate change, which inevitably affects tree growth and various other ecological processes. While the impacts of droughts on these processes have been widely evaluated, the effects of heatwaves on tree growth and soil water content (SWC) remain poorly understood, particularly those related to thinning treatment. In this study, we evaluated the impacts of the 2021 Pacific Northwest Heatwave and thinning on forest growth and SWC, as well as assessed how thinning might mitigate the heatwave's impacts in lodgepole pine forests in British Columbia, Canada. We measured meteorological data (air temperature, rainfall, solar radiation (SR), relative humidity (RH), and wind speed (W_s)), sap flow, SWC, soil temperature (T_s), and tree diameters at the breast height (DBH) during the growing season (June–September) in the control (27,000 stems·ha^{-1}), lightly thinned (4,500 stems·ha^{-1}), and heavily thinned (1,100 stems·ha^{-1}) experimental plots from 2018 to 2024. We found that thinning persistently and significantly ($p < 0.05$) increased individual tree growth, with the most pronounced effects in the heavily thinned stands. The 2021 Pacific Northwest Heatwave led to an exceptionally hot growing season, significantly ($p < 0.05$) reducing forest growth and SWC across all plots. Forest growth recovered in 2022 in the thinned plots but remained suppressed in the unthinned plots, suggesting that thinning effectively mitigated the impact of the heatwave on forest growth, while the heatwave's impacts were persistent in the unthinned plots. Our study highlights that thinning is a practical management strategy for improving tree growth and supporting climate change adaptation to extreme climate events.

1. Introduction

The Earth's climate is undergoing considerable changes. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, AR6), the global surface temperature was 1.09 °C higher in 2011–2020 compared to 1850–1900 (IPCC, 2023). Extreme precipitation events are projected to increase significantly in many regions around the globe (Slater et al., 2024). Given the widespread, rapid, and intensifying climate warming, more extreme climate events (e.g., prolonged droughts, heatwave, and flooding) are anticipated (Maraun et al., 2025). Heatwaves, defined as a period of extremely high temperature that usually lasts two or more days (White et al., 2023), typically occur as compound events, characterized by extreme temperature, low precipitation, and high evaporative demand (Zscheischler et al., 2018). As climate change and warming accelerate, heatwaves are becoming more frequent and severe (Fischer et al., 2021). For example, Barriopedro et al. (2011) revealed that the frequency and intensity of heatwaves have significantly increased between 2003 and 2010. There was also a significant increase in the frequency of marine heatwaves in most ocean regions of the world from 1982 to 2020 (Zhang et al., 2022). Given these trends, understanding how forest ecosystems and processes (e.g., tree growth and soil water content (SWC)) respond to extreme climate

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events, particularly heatwaves, is critically needed for supporting forest and water management for climate change adaptation.

Extreme climate events inevitably affect the health and resilience of forest ecosystems, such as forest growth and productivity (Parra and Greenberg, 2024; Yang et al., 2023a), soil processes such as SWC (Yin et al., 2024), and soil biodiversity (Preece et al., 2019). For example, the area of global land affected by multiyear droughts increased between 1980 and 2018, resulting in considerable declines in vegetation greenness (Chen et al., 2025) and SWC (Yin et al., 2024). While the negative impacts of droughts on forest growth and SWC have been extensively evaluated (Abel et al., 2024; Baldrian et al., 2023; Bevacqua et al., 2024; Chen et al., 2025), the impacts of heatwaves on forest ecosystems are unclear, with positive (Li et al., 2021), negative (Rohner et al., 2021), and neutral (Scharnweber et al., 2020) responses across biomes, tree species, and spatial scales. For example, while the 2003 European Heatwave led to large reductions in gross primary production in temperate deciduous beech and northern Mediterranean forests (Ciais et al., 2005), the 2018 European Heatwave did not constrain stem growth but stems experienced temporary shrinkage due to depletion of water reserves (Salomón et al., 2022). Heatwaves might dramatically affect plant growth via regulating stomatal closure, drying up soils, and consequently inhibiting photosynthesis (Salomón et al., 2022) and exerting strong and sometimes irreversible impacts on forest growth (Yin et al., 2023). In general, trees respond to heatwaves rapidly (Shi et al., 2021), but the understanding of post-heatwave tree growth and other ecological processes remains limited.

Thinning reduces stand density and competition, allowing the remaining trees to grow faster and improve vigor with lower water consumption (del Campo et al., 2022; Wang et al., 2019). It is widely recognized as a practical tool for mitigating the impacts of climate change (del Campo et al., 2019). For example, Sohn et al. (2016) conducted a meta-analysis and found that thinning can improve the physiological and growth response of trees to drought. In general, thinning can promote growth of the targeted tree species and enrich biodiversity (Chase et al., 2016), while sustaining more water resources. In addition, it optimizes water use by regulating key hydrological processes, such as precipitation partitioning, transpiration, and soil moisture (Gebhardt et al., 2014). A global synthesis has identified an optimal thinning intensity of 50% of tree removal as a threshold for significant changes in hydrological processes based on 251 observations globally (del Campo et al., 2022). More importantly, thinning improves the ability of remaining trees to better cope with climate change. It promotes tree vigor that may be helpful in withstanding insect attacks due to climate warming (Chase et al., 2016). Furthermore, thinning combined with prescribed or pile burning can effectively reduce wildfire severity (Brodie et al., 2024; Davis et al., 2024). Despite the benefits of thinning for climate change adaptation, the role of thinning in promoting forest growth and sustaining water resources under extreme climate events (i.e., heatwaves) is rather limited.

In late June 2021, the Pacific Northwest region of Canada and the United States experienced an unprecedented heatwave, marked by record-breaking temperatures and severe heat stress (Jeong et al., 2024; White et al., 2023). This extreme heatwave event resulted in considerable natural and human impacts, including fatalities, marine life casualties, agricultural setbacks, and wildfires. Specifically, the 2021 Pacific Northwest Heatwave caused more than 1,400 human deaths, with approximately 800 in western Canada and 600 in Washington and Oregon, USA (White et al., 2023). Additionally, it contributed to severe environmental disasters, e.g., catastrophic wildfires. On June 29, 2021, the heatwave caused the air temperature to reach 49.6 °C in Lytton (50° N), British Columbia (BC), Canada, contributing to a devastating wildfire on June 30, 2021, which destroyed 90% of the community. Extensive assessments have examined the drivers, mechanisms, and severity of the 2021 Pacific Northwest Heatwave (Jeong et al., 2024; McKinnon and Simpson, 2022; Schumacher et al., 2022; White et al., 2023). However, few studies have evaluated its ecological and hydrological impacts (Conrick and Mass, 2023), and none have specifically investigated tree physiological responses to thinning during and after the heatwave. Long-term forest experimental plots could provide an excellent opportunity to assess the heatwave's impacts on tree growth and other ecological and hydrological processes.

The Upper Penticton Creek (UPC) paired watershed experiment in the southern interior of British Columbia, Canada, was established in the early 1980s to evaluate the impacts of timber harvesting on hydrology, e.g., water quantity and quality (Winkler et al., 2021). Within the paired watersheds, a long-term experimental trial was established in 2016 to assess the effects of thinning treatments on forest growth, climate, and hydrological processes in young and dense lodgepole pine forests. This experiment has generated useful insights into the effects of thinning on tree growth (Wang et al., 2019), water use efficiency (Wang et al., 2020), and water sourcing (Ellis et al., 2024). The 2021 Pacific Northwest Heatwave caused the hottest growing season on record since 2016, which provides an opportunity to examine how the heatwave might affect tree growth and hydrological processes. Using seven-year observational data from 2018 to 2024 during the growing season (June–September), we evaluated the effects of the 2021 Pacific Northwest Heatwave on forest growth and SWC in both thinned and unthinned (control) stands.

In this study, we aimed to address these key questions: (1) How did forest growth and SWC respond to thinning over a seven-year period? (2) How did forest growth and SWC respond to the 2021 Pacific Northwest Heatwave? (3) What role did thinning play in mitigating forest growth responses to the heatwave? Existing studies have revealed a positive role of thinning in individual tree growth and soil moisture (del Campo et al., 2022). Thus, we hypothesized that (1) unthinned stands would exhibit slower growth and lower SWC; (2) the 2021 Pacific Northwest Heatwave would negatively affect forest growth and SWC; and (3) thinning would support the recovery of forest growth following the heatwave. To test these hypotheses, we compared tree growth (represented by diameters at the breast height (DBH)) and SWC between unthinned and thinned plots, assessed differences in forest growth and SWC between the normal climate and heatwave year, and evaluated how thinning influenced forest growth following the heatwave. The findings from these analyses can offer critical insight for forest management, particularly in applying thinning as a strategy to support climate change adaptation in the face of extreme events.

2. Materials and methods

2.1. Study site and thinning treatments

The study site (49°39′39″ N, 119°23′35″ W, 1,675 m a.s.l.) is located in the 241 Creek watershed, part of the UPC paired watershed experiment in the southern interior of British Columbia, Canada (Fig. 1). The study site has a cold winter and cool summer with approximately 60% of total precipitation falling as snow (Winkler et al., 2021). From 1991 to 2019, the long-term mean annual temperature and precipitation were 2.0 °C and 783 mm, respectively, while during the growing season from June to September, the corresponding values were 10.5 °C and 225 mm, respectively. The study site is on a south-facing aspect, and the average slope is 7°. The elevation is 1,675 m. The study site is situated in the Engelmann spruce subalpine fir (ESSF) biogeoclimatic zone (Lloyd et al., 1990; Winkler et al., 2021), and is composed mostly of lodgepole pine (*Pinus contorta* Dougl.) with minor Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) present as secondary growth.

The 241 Creek experienced four major harvesting treatments from 1992 to 2006. From 1993 to 1998, approximately 6% of the 241 Creek watershed was logged to salvage trees toppled during a severe wind storm and construct main roads. The second harvesting operation occurred in late 1998, resulting in an additional 12% forest cover loss and bringing the cumulative total to 18%. The third treatment was

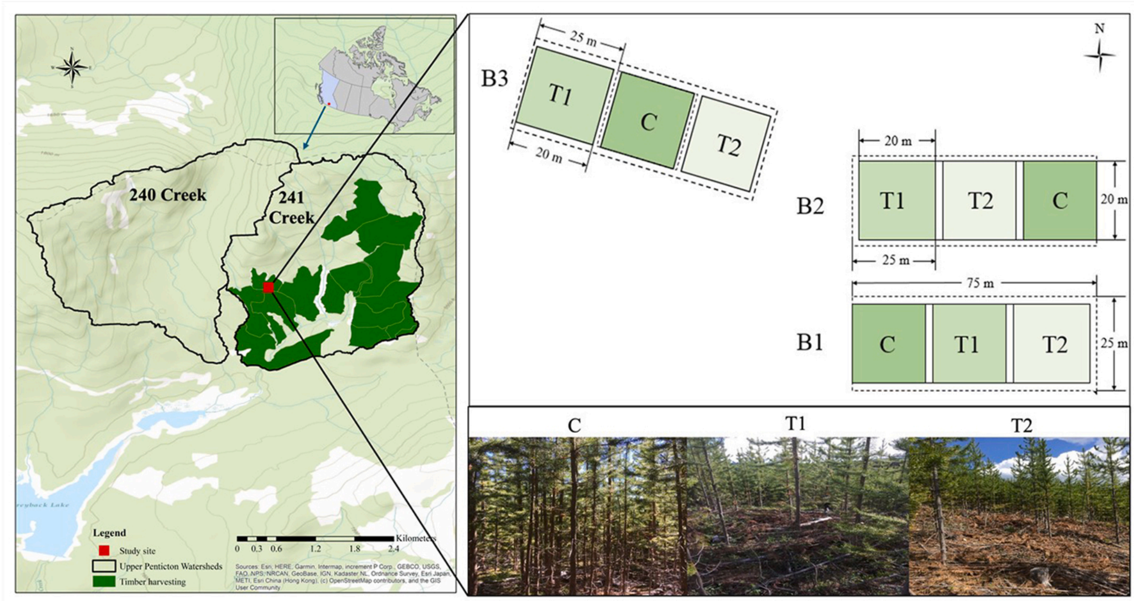

Fig. 1. Study site and plot conditions. Note: B1, B2, and B3 denote Block 1, Block 2, and Block 3; and C, T1, and T2 denote unthinned control, lightly thinned, and heavily thinned plots, respectively.

completed in winter 2002/2003, removing another 10% of the forest and increasing total forest loss to 28%. The last harvesting treatment with an additional 20% of forest removal took place in the winter of 2006/2007, resulting in a total of 47% of the forest removal in the 241 Creek watershed (Winkler et al., 2021). Even-aged lodgepole pine forests were subsequently regenerated with some young Engelmann spruce and subalpine fir.

In June 2016, thinning treatments were applied to the 2002/2003 cutblock containing even-aged lodgepole pine forests (site index = 12). Three blocks, i.e., B1, B2, and B3, with the size of 25 m × 75 m were selected in the field (Fig. 1). Within each block, two thinning treatments (20 m × 20 m), including a lightly thinned treatment (T1) and a heavily thinned treatment (T2), along with an unthinned control (C) plot were established. Following the treatments, the tree densities were 27,000 stems·ha^{-1} for C, 4,500 stems·ha^{-1} for T1, and 1,100 stems·ha^{-1} for T2 plots (Wang et al., 2019).

2.2. Meteorological data

HOBO weather stations (Onset Computer, Bourne MA, USA) were installed in three plots in B1. For C, variables including air temperature (T, °C) and relative humidity (RH, %) were monitored from 2018 to 2022. Unfortunately, this weather station was destroyed by wild animals in September 2022, and data were unavailable afterward. In T1, the monitored variables included T, RH, solar radiation (SR, W·m^{-2}), and wind speed (W_s, m·s^{-1}). In T2, a rain gauge was included to measure rainfall (P, mm) in addition to T, RH, SR, and W_s. The meteorological conditions in T1 and T2 were recorded from 2018 to 2024. All meteorological variables were measured at a 10-min time interval.

In 2018 and 2019, the HOBO weather station in T2 experienced power supply issues, resulting in discontinuous measurements and data gaps for rainfall. To address this, rainfall data from a station (P1: 49°39′05″ N, 119°23′56″ W; 1,620 m a.s.l.) near the outlet of the 241 Creek and operated by the BC Ministry of Forests (Moore et al., 2021; Winkler et al., 2021) were used. Linear regression relationships between daily rainfall at T2 and P1 were established for non-gap days in 2018 (R^2 = 0.95) and 2019 (R^2 = 0.84). These relationships were then used to estimate and fill the missing rainfall data for gap days.

To identify heat and cold conditions, growing season air temperatures and their anomalies (a departure from the average) were calculated. To characterize drought and wet conditions, the standardized precipitation index (SPI) was calculated based on rainfall during the growing seasons (Guttman, 1999; Tian et al., 2018). The meteorological data in the growing season from 2018 to 2024 were used to identify extreme climate events (Section 3.1).

2.3. Soil water content and soil temperature data

In June 2021, TEROS 11 advanced soil moisture and temperature sensors (METER Group, Inc., USA) were installed to monitor SWC and soil temperature (T_s) in B1. In each plot, two sensors were installed at a depth of 10–15 cm, and the other two at 35–40 cm, resulting in four sensors per plot. The data were recorded at 15-min intervals using ZL6 data loggers (METER Group, Inc., USA).

2.4. Forest growth measurement

Forest growth was quantified as the diameters at the breast height (DBH). In each plot, 45 trees of similar diameter size distributions were selected for long-term monitoring. After the initial selection and measurement in 2016, the same trees were measured at the end of the growing season annually. DBH were measured using an electronic caliper (Mitutoyo Corporation, Japan), totaling 405 trees (45 sample trees × 3 plots × 3 blocks) in all experimental plots. For each measurement, tree DBH were recorded three times per tree, and the average value was used as the DBH for that year. The annual change in DBH, calculated as the difference between the current season's measurement and that of the antecedent season, was used to represent tree growth.

2.5. Paired-year approach and statistical analysis

This study applied the paired-year approach to examine how extreme climate events, particularly the heatwave, affect hydrological responses (i.e., SWC, T_s, and transpiration). The paired-year approach assumes that changes in response variables are attributed to one factor when other factors between the reference and disturbance year are similar or comparable (Wang et al., 2013; Zhang et al., 2016). In this study, only the heatwave or extremely wet condition are considered as the dominant difference between the paired years, while other factors (e.g., precipitation and temperature) remain similar when evaluating the effects of extreme climate events on SWC, T_s, and transpiration. Despite potential lasting effects of extreme events on SWC, existing studies have indicated relatively short recovery times of several months (e.g., less than 7 months) (Shao et al., 2024; Yao et al., 2023). This method pairs a reference year with a disturbed year that exhibits significantly different conditions in specific climate variables (e.g., temperature) while maintaining similarity in other variables (e.g., rainfall; Zhang et al., 2016). By controlling for rainfall variability, we are able to evaluate the influence of the heatwave on hydrological variables. Three pairs of normal climate conditions and extreme climate conditions were selected in this study to address our research questions (Section 3.1).

The nonparametric Mann–Whitney *U* test was applied to identify statistically significant differences in forest growth between treatments and between years, as well as to detect statistically significant differences in hydrological variables between paired years. The Mann–Whitney *U* test has no specific assumptions about data distribution (Mann and Whitney, 1947), which has been widely used in hydrological and ecological studies to test the differences between the two groups (Aryal and Zhu, 2020; Gottardini et al., 2020). The significance level was set at 0.05 in this study. Given the presence of missing values, we employed the paired option in the Mann-Whitney *U* test to ensure that comparisons were made only between matched data points for each pair. Using measured DBH from all trees within a given treatment (3 blocks × 45 trees = 145 trees in each treatment), three pairwise comparisons were made between treatments (i.e., C vs. T1, C vs. T2, and T1 vs. T2) in each year to evaluate the effects of thinning on forest growth, while multiple pairwise comparisons between two years were conducted to evaluate the effects of climate conditions on forest growth. As for SWC, T_s, and transpiration, the pairwise comparison between a normal climate year and an extreme climate year in each treatment was made.

3. Results

3.1. Growing season meteorological conditions and extreme climate events

The daily and seasonal dynamic of meteorological variables can be found in Section S1. The growing season climate conditions varied considerably from 2018 to 2024 (Fig. 2). Air temperatures and their anomalies (a departure from the average) revealed a distinct trend, showing that growing seasons before 2021 were cooler than the long-term average, whereas those after 2021 were warmer (Fig. 2a). The 2019 growing season was the coolest, with air temperatures approximately 1.5 °C below the long-term average. In contrast, the 2021 growing season was the hottest, with an average air temperature of 12.6 °C, about 1 °C higher than in the growing seasons of the other years (Fig. 2a). The 2021 Pacific Northwest Heatwave, which occurred at the end of June (Jeong et al., 2024; White et al., 2023), caused the daily air temperature to peak at 27.6 °C on June 29 (Fig. S1). As a result, the monthly temperature in June and July 2021 rose to 12.5 and 16.7 °C, respectively. In contrast, the corresponding monthly temperatures in June and July in other years were 9.4 and 13.8 °C, respectively. More specifically, during the heatwave (June 25 to July 2, 2021), air temperature reached 24 °C, while the corresponding value was 11 °C for the same week in other years (Fig. S1). This means that the heatwave raised daily temperatures by approximately 13 °C during the event.

In addition to temperature variations, growing season rainfall differed among years. From 2018 to 2024, the average rainfall was 162 mm, ranging from 94 mm in 2018 to 293 mm in 2022 (Fig. 2b). The highest daily rainfall was recorded on June 13, 2022, with the value of 48.6 mm. Surprisingly, despite the 2021 Pacific Northwest Heatwave, the SPI value of −0.74 suggested it did not result in meteorological drought in 2021 growing season. The SPI indicated that the 2019 and 2022 growing seasons were moderately wet (1.0 < SPI <1.5) (Khan et al., 2020) with SPI values of 1.22 and 1.46, respectively (Fig. 2c). Based on these analyses, three growing seasons were identified as distinctive climates: 2019 was cool and moderately wet, 2021 was hot due to the heatwave, and 2022 was moderately wet.

With similar rainfall and SPI, we selected the pair of 2021 (heatwave) and 2023 (normal climate) growing seasons to evaluate the effects of the heatwave on SWC, T_s, and transpiration (Table 1). Additionally, pairs representing normal climate conditions (2018 and 2023) and moderately wet conditions (2019 and 2022) of years before and after the heatwave were selected to compare transpiration differences across plots to assess the potential lasting effects of the heatwave (Table 1).

3.2. Impacts of thinning on forest growth and SWC

DBH increments, representing forest growth, were significantly ($p <$ 0.05) different among thinned and control plots (Fig. 3). From 2018 to 2024, DBH increments were significantly ($p < 0.05$) higher in T2 with the mean value of 4.1 mm, ranging from 3.7 to 4.6 mm. In contrast, C exhibited the lowest DBH increments, with a mean of 1.8 mm (ranging from 1.4 to 2.2 mm). T1 showed intermediate growth, with DBH increments ranging from 2.7 to 3.5 mm and averaging 3.1 mm. These

Table 1
Selected pairs with extreme and normal climate conditions for the paired-year analysis.

No.	Pair		*T* (°C)	*T* anomaly (°C)	*P* (mm)	SPI
1	Heatwave	2021	12.57	0.98	143	−0.74
	Normal climate	2023	11.90	0.31	137	−0.86
2	Normal climate	2018	11.59	0.00	157	−0.49
	Moderately wet	2019	10.20	−1.40	272	1.22
3	Moderately wet	2022	12.31	0.72	293	1.46
	Normal climate	2023	11.90	0.31	137	−0.86
4	Moderately wet	2019	10.20	−1.40	272	1.22
	Moderately wet	2022	12.31	0.72	293	1.46

Note: *T*, *P*, and SPI denote growing season air temperature, precipitation, and standardized precipitation index, respectively.

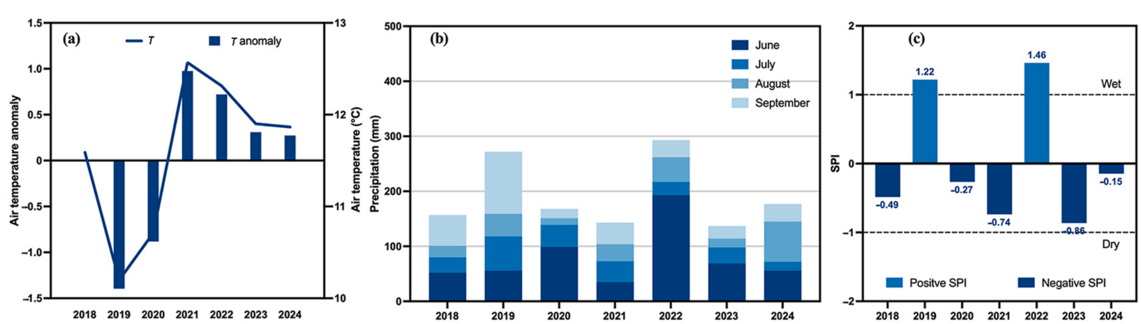

Fig. 2. Growing season **(a)** air temperature and air temperature anomaly, **(b)** precipitation, and **(c)** standardized precipitation index (SPI) from 2018 to 2024.

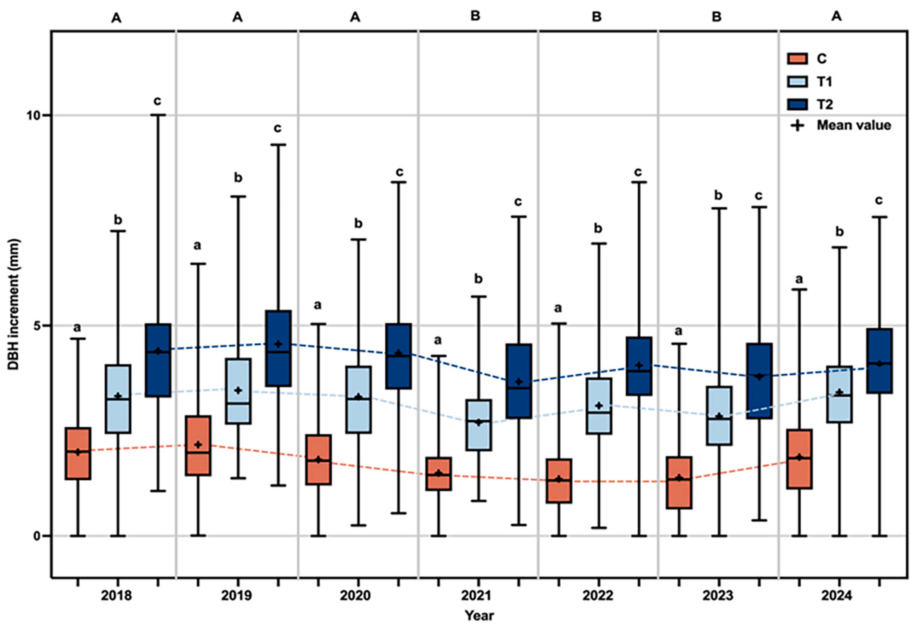

Fig. 3. DBH increment in C, T1, and T2 plots from 2018 to 2024. Note: Different lowercase letters indicate significant differences in DBH increments among different plots in each year, and different uppercase letters denote significant differences in DBH increments from all plots among different years. C, T1, and T2 denote unthinned control, lightly thinned, and heavily thinned plots, respectively.

results clearly indicated that thinning can significantly increase forest growth, with more pronounced effects in more heavily thinned stands.

Since soil data were unavailable before 2021, we compared daily SWC and T_s in normal climate years (2023 and 2024) to evaluate the impacts of thinning (Fig. 4). During these years, SWC did not differ significantly ($p > 0.05$) among the plots (Fig. 4a), with average daily values of 0.14 $m^3 \cdot m^{-3}$ in C, 0.15 $m^3 \cdot m^{-3}$ in T1, and 0.15 $m^3 \cdot m^{-3}$ in T2. In contrast, T_s were significantly ($p < 0.05$) different in C, T1, and T2 (Fig. 4b). C had the lowest daily T_s (average of 10.5 °C), followed by T1 (average of 11.7 °C), while T2 exhibited the highest daily T_s (average of 12.7 °C) (Fig. 4b). These results indicate that while thinning did not significantly impact SWC after eight years, it significantly increased T_s, with more pronounced effects in the more heavily thinned stands.

3.3. Impacts of the heatwave on forest growth and SWC

When DBH increments from all plots were combined and grouped by years, Fig. 3 shows that DBH increments were significantly ($p < 0.05$) lower from 2021 to 2023 than from 2018 to 2020. The average DBH increment in 2021 was 2.61 mm, while the average corresponding value for the other years was 2.75 mm. This suggests that the 2021 Pacific Northwest Heatwave had a significant and negative impact on forest growth.

To evaluate the impacts of the heatwave on tree growth in the unthinned and thinned stands, we replotted and reanalyzed DBH increments grouped by treatment types (Fig. 5). In C, DBH increments in 2021–2023 were significantly ($p < 0.05$) lower than the other years (i.e., 2018, 2019, 2020, and 2024). In T1 and T2, DBH increments were significantly ($p < 0.05$) lower only in 2021, with average values of 2.7 mm in T1 and 3.67 mm in T2. In 2022, DBH increments in T1 and T2 were significantly ($p < 0.05$) higher than those in 2021, while there was no significant ($p > 0.05$) difference in DBH increments in C (Fig. 5). These findings suggest that forest growth recovered from the 2021 Pacific Northwest Heatwave in the thinned plots in 2022, while the heatwave had a lasting impact in the control plots until 2024.

This study applied the paired-year approach and compared the 2021 and 2023 growing seasons, which had similar rainfall amounts and SPI but different temperature anomalies (0.98 in 2021 vs. 0.31 in 2023) (Fig. 2 and Table 1), to assess the impacts of the heatwave on SWC and T_s. Significant differences were observed between these two years (Figs. 6 and 7). At the daily scale, SWC increased following rainfall events (Fig. 6b and c). However, SWC was significantly ($p < 0.05$) lower during the heatwave (2021) than in the normal climate condition year (2023) in all plots (Fig. 6a). In 2021 with the heatwave, the average growing season SWC was 0.10 $m^3 \cdot m^{-3}$ in C, 0.11 $m^3 \cdot m^{-3}$ in T1, and 0.12 $m^3 \cdot m^{-3}$ in T2, while the corresponding values in 2023 were 0.12, 0.13, and 0.16 $m^3 \cdot m^{-3}$, respectively. SWC in 2021 was significantly ($p <$

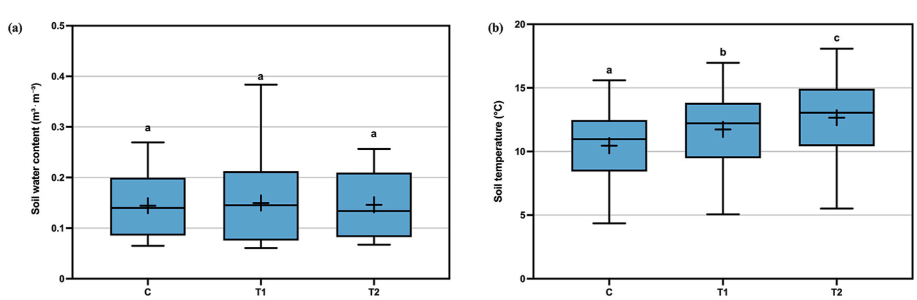

Fig. 4. Daily **(a)** soil water content (SWC) and **(b)** soil temperature (T_s) in normal climate years (2023 and 2024). Note: Different lowercase letters indicate significant differences. C, T1, and T2 denote unthinned control, lightly thinned, and heavily thinned plots, respectively.

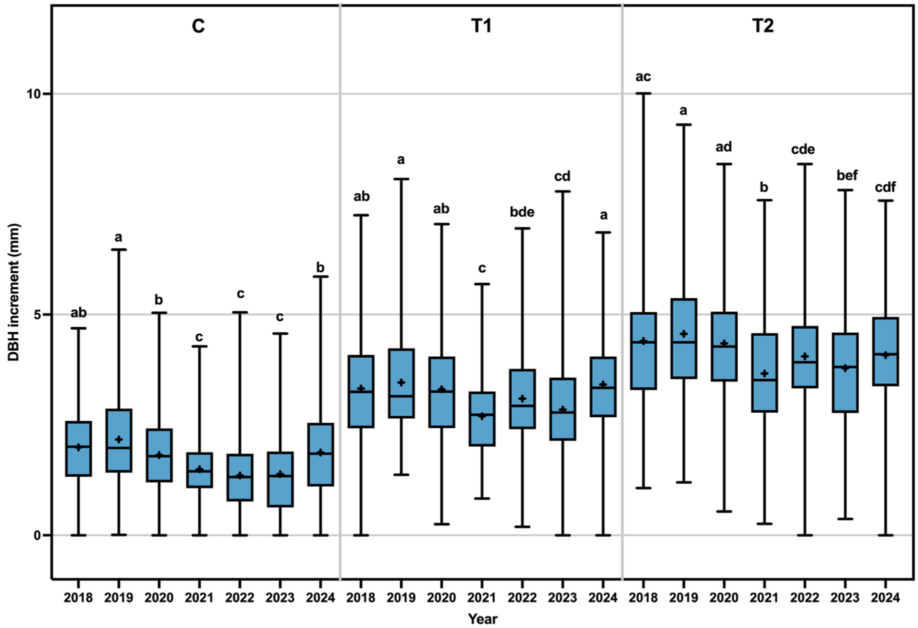

Fig. 5. Forest growth (DBH increment) from 2018 to 2024 across C, T1, and T2 plots. Note: Different lowercase letters denote significant differences in DBH increments between years. C, T1, and T2 denote unthinned control, lightly thinned, and heavily thinned plots, respectively.

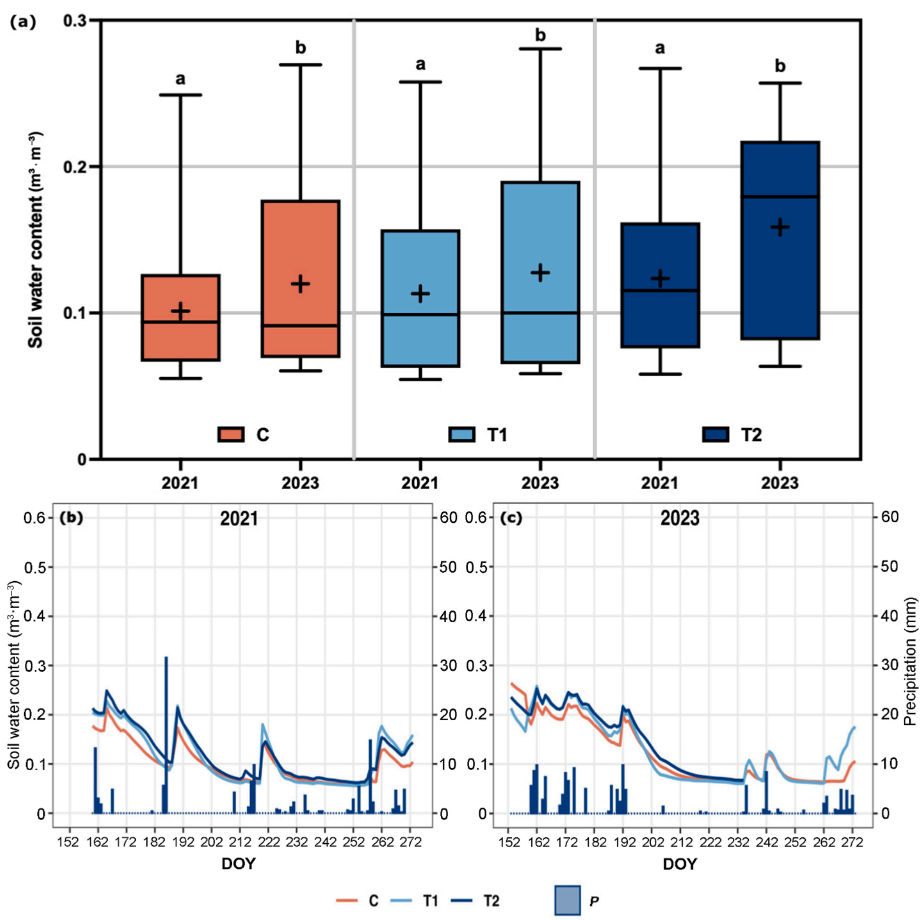

Fig. 6. **(a)** Daily soil water content in growing seasons of 2021 (heatwave) and 2023 (normal climate year), and temporal dynamics of daily soil water content and precipitation in **(b)** 2021 and **(c)** 2023. Note: Different lowercase letters denote significant differences in soil water content between 2021 and 2023. C, T1, and T2 denote unthinned control, lightly thinned, and heavily thinned plots, respectively. DOY denotes day of the year.

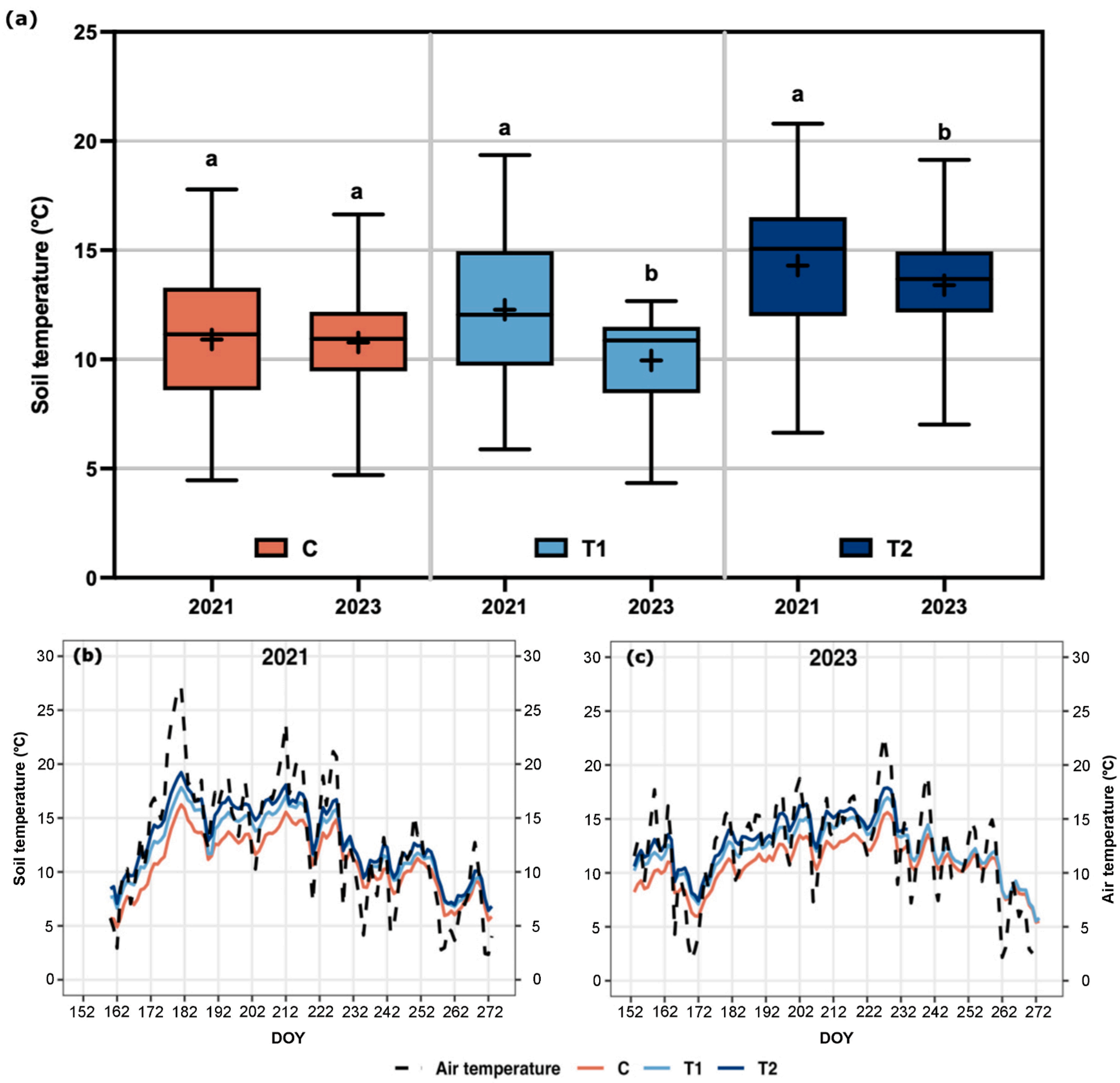

Fig. 7. **(a)** Daily soil temperature in growing seasons of 2021 (heatwave) and 2023 (normal climate year), and temporal dynamics of daily soil temperature and air temperature in **(b)** 2021 and **(c)** 2023. Note: Different lowercase letters denote significant differences in soil temperature between 2021 and 2023. C, T1, and T2 denote unthinned control, lightly thinned, and heavily thinned plots, respectively. DOY denotes day of the year.

0.05) lower by 15.5%, 11.4%, and 22.2% than those in 2023 (Fig. 6a), suggesting that the heatwave significantly decreased SWC.

The variations in T_s closely reflected the patterns of air temperature (Fig. 7b and c). During the heatwave (2021), T_s were significantly ($p < 0.05$) higher by 2.3 and 0.9 °C in T1 and T2, respectively, than in the normal climate condition year (2023). In contrast, T_s in C showed a non-significant difference ($p > 0.05$) between 2021 and 2023 (Fig. 7a).

4. Discussion

4.1. Long-term responses of tree growth and SWC to thinning

Our analysis shows that DBH increments were persistently and significantly ($p < 0.05$) higher in T1 and T2 than those in C from 2018 to 2024, with more pronounced effects in T2 (Fig. 3). The result supports Hypothesis 1 regarding tree growth. These results clearly suggest that thinning persistently enhances tree growth over the study period, which is consistent with other studies (del Campo et al., 2019; Zhang et al., 2024). Thinning decreases stand density, thereby decreasing competition for water, energy (e.g., light and solar radiation), and nutrients among trees (Chase et al., 2016), ultimately promoting the growth of remaining individual trees (Zhang et al., 2024). With more available solar radiation in T1 and T2 (Fig. S1), tree growth is promoted. Using the measured volumetric data on SWC, Wang et al. (2019) found that SWC initially increased in the same thinned plots compared to the control plots following the thinning treatments in 2016 and 2017. All these findings suggest that thinning reduces competition for resources, allowing more radiation and water availability, which in turn promotes tree growth. Although soil nutrients were not measured in this study, we expect that more nutrients should be available after thinning (Zhou et al., 2019).

Interestingly, eight years after thinning treatments, SWC in C, T1, and T2 in the growing seasons showed no significant difference ($p > 0.05$) during normal climate condition years, i.e., 2023 and 2024 (Fig. 4a), despite an initial increase in SWC in T1 and T2 in 2016 and 2017 following the treatments (Wang et al., 2019). These results reject Hypothesis 1 regarding SWC. These results suggest an offset between decreased transpiration and increased soil evaporation in the plots. Thinning opens the canopy, resulting in reduced canopy interception and increased throughfall, allowing more water to infiltrate and recharge the soil. Additionally, decreased stand density and stand-level transpiration (Fig. S2) lower overall water demand for tree growth, contributing to higher SWC in the thinned stands in the first years after thinning. A global review of thinning impacts on key hydrological processes found that, in most cases, thinning initially increased soil moisture (del Campo et al., 2022). However, as canopy cover decreases in the thinned plots, increased T_s (Fig. 4b) and greater exposure to solar radiation can promote soil evaporation, which can reduce SWC. Our data indicated that the growing season has shifted from a cool phase to a warm phase since 2021 (Fig. 2a), leading to persistently higher evaporative demand. As a result, the increased evaporation in the thinned plots likely offsets the gains in SWC due to lower transpiration, ultimately leading to no significant differences in SWC between the thinned and control plots in 2023 and 2024. A global study analyzing 404 observations has also found that soil moisture changes due to thinning were generally non-significant (Zhang et al., 2018), particularly in coniferous forests.

T_s in T1 and T2 were significantly ($p < 0.05$) higher than those in C, with the most pronounced increase observed in T2 (Fig. 4b). This supports the role of increased soil evaporation in regulating SWC. The increased T_s after thinning has been widely evaluated in existing studies (Chase et al., 2016; del Campo et al., 2022; Zhang et al., 2024; Zhou et al., 2020). In general, T_s tends to increase with thinning intensity (Zhang et al., 2018). This is due to the removal of tree canopy, which exposes the forest floor to greater direct sunlight and solar radiation (Zhang et al., 2023), thereby increasing albedo (Kellomäki et al., 2023), warming the soil surface, and increasing T_s. Over time, the effect of thinning on T_s is expected to diminish as the forest recovers (Zhang et al., 2018). The gradual growth of understory vegetation and remaining trees can reduce canopy gaps, providing increased shading and moderating T_s. However, even after eight years following the thinning treatments in our study plots, large canopy openings persist in T1 and T2, preventing significant mitigation of increased T_s.

Our incomplete data on tree-level water consumption and stand-level transpiration further provide useful evidence to support the role of decreased transpiration in regulating SWC (Fig. S2). We found that tree-level water consumption (transpiration) was significantly ($p < 0.05$) higher in T1 and T2 than in C, but it was significantly ($p < 0.05$) larger in T1 compared with T2 in 2022 and 2023 (Fig. S2a). At the stand level (Fig. S2b), transpiration was consistently and significantly ($p < 0.05$) higher in C as compared with T1 and T2, while no significant difference between T1 and T2 in 2023. The lower tree-level water consumption and higher stand-level transpiration in C align with previous findings, which show that reduced stand density leads to increasing of tree-level water consumption while decreasing of stand-level transpiration (del Campo et al., 2022; Gebhardt et al., 2014; Skubel et al., 2017). In C, greater competition among trees results in lower water consumption at the individual tree level, while the higher stand density ultimately contributes to greater stand-level transpiration, and thus leads to lower SWC. After seven and eight years of the thinning treatments (2022 and 2023), stand-level transpiration is still low in T1 and T2, potentially increasing SWC. Interestingly, as not expected, tree-level water consumption in T2 was significantly ($p < 0.05$) lower than in T1 in 2022 and 2023. Similarly, Li et al. (2023) found that the plot with moderate competitive pressures had higher transpiration than the plot with low competitive pressures under spring drought in the southern Liupan Mountains, Northwest China. This may probably result from the reduced difference in vapor pressure deficit among competitive pressure levels. In addition, the rapid growth of understory vegetation in T2 might be a factor affecting SWC. It competes with remaining trees for water and energy, thereby reducing the availability of water for tree growth (Gebhardt et al., 2014). Although understory vegetation was sparse immediately after thinning and had minor effects (Wang et al., 2019), it might become an important factor influencing water availability over the long term, requiring further research.

4.2. Effects of the heatwave on tree growth and SWC

The 2021 Pacific Northwest Heatwave significantly ($p < 0.05$) constrained forest growth in all plots (Figs. 3 and 5). The result supports Hypothesis 2 regarding tree growth. Heatwaves would cause extremely high temperatures, which are the key factor influencing tree growth. As shown in Fig. 2a, the 2021 growing season was the hottest recorded, with the growing season T and T anomaly being 12.6 and 0.96 °C, respectively, largely driven by the extreme heat in June. The 2021 Pacific Northwest Heatwave resulted in high air temperatures reaching 12.5 °C in June in comparison with an average of 9.4 °C in the other years. During the heatwave (June 25 to July 2, 2021), the air temperature reached 24 °C, while the corresponding value was 11 °C in other years (Fig. S1). Although no meteorological drought occurred due to the heatwave in the 2021 growing season (Fig. 2), the heatwave and associated extreme temperatures led to significantly ($p < 0.05$) lower SWC (Fig. 6), suggesting a potential hydrological drought (Shi et al., 2022). This implies reduced water availability for tree growth. Additionally, heatwaves and associated extreme temperatures might influence tree growth by regulating stomatal conductance and photosynthesis. Extremely high temperatures during heatwaves are typically accompanied by high vapor pressure deficits, which reduce stomatal conductance, thereby limiting photosynthesis (Grossiord et al., 2020). It is evident that there is a temperature optimum curve for photosynthesis, showing that temperature increases enhance photosynthesis and prolong the growing season up to the temperature optimum, promoting tree growth, beyond which photosynthesis declines, reducing tree growth (Crous et al., 2022). In a global study, the temperature optimum for forest growth in our study region is about 20 °C (Chen et al., 2021). The average temperature in the study site during the heatwave period (24 °C) is above this temperature optimum, which could severely affect forest growth. Moreover, severe temperature extremes can scorch leaves in extreme cases, leading to tree die-off (Larcher, 2003). However, studies on the effects of heatwaves and extreme temperatures on forest growth have shown inconsistent results on tree growth. For example, Salomón et al. (2022) found that stem growth was not consistently decreased due to the 2018 European Heatwave, while the heatwave led to stem dehydration. Despite consistently reduced radial growth resulting from daytime, nighttime, and compound hot extremes in dry regions globally, radial growth was increased by nighttime and compound hot extremes, while it was decreased by daytime hot extremes in humid regions (Yang et al., 2023b). Generally, heatwaves are combined with drought and can affect tree growth, which further inhibits photosynthesis and carbon uptake (Salomón et al., 2022).

Our results also showed that the 2021 Pacific Northwest Heatwave significantly ($p < 0.05$) reduced SWC in both control and thinned plots (Fig. 6), supporting Hypothesis 2 regarding SWC, while significant increased T_s were only found in thinned plots (Fig. 7). These results suggest that the heatwave consistently increased T_s and consequently caused reduction of SWC due to increased soil evaporation in thinned plots. However, the non-significant difference in T_s in C was mainly due to the dense forest cover with a larger overstory and ground biomass, creating a more stable microclimate with less temperature fluctuation. The dense canopy and ground litter could act as a barrier, blocking shortwave and longwave radiation from the atmosphere (Vose et al., 2011). Given the non-significant difference in T_s in the unthinned plots, the reduction of SWC in C during the heatwave growing season was mainly due to an increase of transpiration, which requires verification in future studies.

4.3. Thinning mitigates the impact of the heatwave on forest growth

Fig. 5 shows that DBH increments were significantly ($p < 0.05$) and consistently lower in C from 2021 to 2023, followed by a significant ($p < 0.05$) increase in 2024. In contrast, DBH increments in T1 and T2 were only significantly ($p < 0.05$) lower in 2021 but increased in 2022 with moderately wet conditions. These different responses indicate that thinning helps mitigate the negative effects of the heatwave on tree growth, supporting Hypothesis 3, while the heatwave has a lasting and prolonged negative impact on forest growth in control plots. Following a moderately wet growing season in 2022, the total rainfall doubled compared to 2021, increasing from 143 mm in 2021 to 293 mm in 2022 (Fig. 2 and Table 1). This alleviates the potential hydrological drought from the previous year and increases SWC and water availability for tree growth. After seven years, trees in thinned plots (T1 and T2) have likely experienced shifts in carbon allocation, leading to a well-established growth trajectory that allows them to respond more rapidly to external changes, such as the heatwave and wet. Thus, tree growth in thinned plots recovers more quickly, demonstrating that thinning enhances resilience to extreme climate events and serves as an effective forest management strategy for climate change adaptation. In contrast, trees in C plots are likely more sensitive to external stressors due to greater competition for resources and consequently, their recovery from extreme climate events, such as heatwaves, takes longer.

Our study clearly shows that a cool and moderately wet growing season (2019) promoted transpiration compared with a normal climate growing season (2018) before the heatwave (Figs. S3 and S4). However, a moderately wet growing season (2022) did not facilitate transpiration recovery after the heatwave, as indicated by significantly lower tree-level water consumption and transpiration in 2022 compared to the normal climate year of 2023 (Figs. S3 and S4). Under similar moderately wet conditions (2019 vs. 2022), transpiration in 2019 (before the heatwave) was significantly ($p < 0.05$) higher than in 2022 (after the heatwave) in C and T2 (Fig. S4). The contrasted difference or reversed pattern suggests that the heatwave might have a persistent impact on transpiration in the post-heatwave years. Before the heatwave year, wet years had greater transpiration as compared to those in the normal climate years, which is consistent with the finding from the previous study conducted in the same plots (Wang et al., 2019) and others (Chen et al., 2024; Stojanovic et al., 2017). After the heatwave, trees likely need more time to recover their hydrological functions. In our study site, the tree leaves were severely scorched and damaged by the 2021 Pacific Northwest Heatwave, ultimately resulting in leaf desiccation and abscission, and reducing photosynthesis ability (López et al., 2022). These leaf damages did not recover immediately in the subsequent years after the heatwave, resulting in a reduction of photosynthesis and transpiration. This explains the reversed pattern observed after the heatwave. Nevertheless, thinning is beneficial for forest growth recovery. However, its role in mitigating the negative impacts of extreme climate events on transpiration needs more monitoring and evaluation.

4.4. Management implications

Our assessment from this study continues to show the positive effects of thinning on tree growth and transpiration at the tree level (Figs. 3 and S2). These important results have important implications for managing overstocked young lodgepole pine forests in the interior of British Columbia. This study clearly indicates that thinning is an effective and practical management strategy in young and overstocked lodgepole pine forests. Despite improved individual tree growth through thinning, it decreases total production at the stand level. Clearly, there are potential trade-offs between total carbon or biomass at the stand level and improved growth or economic values of remaining trees after thinning. Thus, determining an optimal thinning density would be more desirable to achieve the balance among various management objectives.

The results from this study also show that thinning can help mitigate the negative impacts of the heatwave on tree growth. This is particularly important to British Columbia as it is facing unprecedented climate change challenges, including increasing wildfire activity and more frequent extreme temperatures. How to cope with climate change, and its induced extreme temperatures and wildfire disturbance, is critical for British Columbia forests to maintain their resilience and long-term sustainability. As dense lodgepole pine forests are vulnerable to extreme temperatures and wildfires, thinning may be an important practice to address these imminent challenges.

4.5. Limitations and future studies

There are some limitations in this study, requiring discussion. Firstly, due to the malfunctioning of sap flow devices, we lacked transpiration data for the heatwave year (2021), preventing a direct evaluation of the impact of the heatwave on transpiration. Secondly, the soil sensors were installed in 2021 summer, which means that we did not have baseline soil conditions before the heatwave. Despite the similar P and SPI in 2021 and 2023, soil conditions in the antecedent non-growing season might be different, resulting in different storage potentials. In spite of these limitations, combining available transpiration and SWC data still provides valuable insights into how hydrological processes (e.g., SWC and transpiration) and forest growth respond to the heatwave. Thirdly, although the existing studies have indicated shorter soil moisture recovery times, findings are primarily based on drought events (Shao et al., 2024; Yao et al., 2023) rather than heatwaves. Thus, there is a level of uncertainty about whether SWC recovers fully from a heatwave when using the paired-year approach to compare data between 2021 and 2023. Given that forest growth in thinned plots had recovered in 2023, we judge that the level of uncertainty caused by the possible lasting effects is low or marginal. Lastly, while the Granier's thermal dissipation probe has been widely used to measure sap flows in many studies (Dix and Aubrey, 2021; Xu et al., 2023), some studies have also indicated that it may underestimate sap flows (Flo et al., 2019; Steppe et al., 2010). This further suggests that additional calibration may be necessary when validation data becomes available. Continuation of long-term field experiments and observations is always challenging due to the impacts of extreme events on the installed devices and the needed maintenance. Despite some unavailable data, we believe the existing data is sufficient to address our research questions effectively.

This study found that thinning can mitigate the negative impact of heatwaves on forest growth (Fig. 5). However, the potential mitigating role of thinning in regulating hydrological processes, e.g., SWC and transpiration, is not verified. Future studies could conduct some experiments to evaluate if there is a mitigating role of thinning in regulating soil water dynamics and transpiration. Additionally, potential geometric effects may influence how biomass production translates into diameter growth. As trees grow, similar biomass increments may result in smaller diameter increases. To address this, future studies are encouraged to measure basal diameter directly and use basal area increment as an indicator of forest growth. Moreover, this study focused solely on the responses of SWC and T_s to thinning, while other important ecological processes, such as soil organic matter and nutrient dynamics, were not monitored. Thinning can increase T_s, which may accelerate litter decomposition. In the short term, this could enhance nutrient release to the soil, but over the long term, it may lead to a reduction in soil organic matter (Yang et al., 2022). Therefore, future research should evaluate the long-term responses of soil ecological processes to thinning.

5. Conclusions

This study provides crucial insights into the effects of thinning and the 2021 Pacific Northwest Heatwave on forest growth and SWC, as well as the role of thinning in mitigating the heatwave's impact. Our findings revealed that thinning significantly and persistently enhanced tree growth, even under the heatwave, suggesting that thinning is more beneficial for improving forest growth. While the heatwave negatively affected forest growth and SWC, thinning helped tree growth recover more quickly, whereas the unthinned stands exhibited prolonged slow growth. Our findings reinforce the importance of thinning as a practical forest management strategy to improve forest resilience to climate change impacts. We conclude that the thinning can provide ecological benefits to young overstocked lodgepole pine forests in British Columbia, Canada.

CRediT authorship contribution statement

Yiping Hou: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaohua Wei:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zhipeng Xu:** Writing – review & editing, Methodology, Investigation, Data curation. **Sheena A. Spencer:** Writing – review & editing, Supervision. **Ming Qiu:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Shixuan Lyu:** Writing – review & editing, Resources, Investigation, Data curation. **Wenfei Liu:** Writing – review & editing, Resources, Investigation, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data are available upon reasonable request.

References

Abel, C., Maestre, F.T., Berdugo, M., Tagesson, T., Abdi, A.M., Horion, S., Fensholt, R., 2024. Vegetation resistance to increasing aridity when crossing thresholds depends on local environmental conditions in global drylands. Commun. Earth Environ. 5 (1), 379. https://doi.org/10.1038/s43247-024-01546-w.

Aryal, Y., Zhu, J., 2020. Effect of watershed disturbance on seasonal hydrological drought: an improved double mass curve (IDMC) technique. J. Hydrol. 585, 124746. https://doi.org/10.1016/j.jhydrol.2020.124746.

Baldrian, P., López-Mondéjar, R., Kohout, P., 2023. Forest microbiome and global change. Nat. Rev. Microbiol. 21 (8), 487–501. https://doi.org/10.1038/s41579-023-00876-4.

Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M., García-Herrera, R., 2011. The hot summer of 2010: redrawing the temperature record map of Europe. Science 332 (6026), 220–224. https://doi.org/10.1126/science.1201224.

Bevacqua, E., Rakovec, O., Schumacher, D.L., Kumar, R., Thober, S., Samaniego, L., Seneviratne, S.I., Zscheischler, J., 2024. Direct and lagged climate change effects intensified the 2022 European drought. Nat. Geosci. 17 (11), 1100–1107. https://doi.org/10.1038/s41561-024-01559-2.

Brodie, E.G., Knapp, E.E., Brooks, W.R., Drury, S.A., Ritchie, M.W., 2024. Forest thinning and prescribed burning treatments reduce wildfire severity and buffer the impacts of severe fire weather. Fire Ecol. 20 (1), 17. https://doi.org/10.1186/s42408-023-00241-z.

Chase, C.W., Kimsey, M.J., Shaw, T.M., Coleman, M.D., 2016. The response of light, water, and nutrient availability to pre-commercial thinning in dry inland Douglas-fir forests. For. Ecol. Manag. 363, 98–109. https://doi.org/10.1016/j.foreco.2015.12.014.

Chen, L., Brun, P., Buri, P., Fatichi, S., Gessler, A., McCarthy, M.J., Pellicciotti, F., Stocker, B., Karger, D.N., 2025. Global increase in the occurrence and impact of multiyear droughts. Science 387 (6731), 278–284. https://doi.org/10.1126/science.ado4245.

Chen, S., Zhang, Z., Chen, Z., Xu, H., Li, J., 2024. Responses of canopy transpiration and conductance to different drought levels in Mongolian pine plantations in a semiarid urban environment of China. Agric. For. Meteorol. 347, 109897. https://doi.org/10.1016/j.agrformet.2024.109897.

Chen, Y., Feng, X., Fu, B., Wu, X., Gao, Z., 2021. Improved global maps of the optimum growth temperature, maximum light use efficiency, and gross primary production for vegetation. J. Geophys. Res. Biogeosci. 126 (4), e2020JG005651. https://doi.org/10.1029/2020JG005651.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437 (7058), 529–533. https://doi.org/10.1038/nature03972.

Conrick, R., Mass, C.F., 2023. The influence of soil moisture on the historic 2021 Pacific Northwest heatwave. Mon. Weather Rev. 151 (5), 1213–1228. https://doi.org/10.1175/MWR-D-22-0253.1.

Crous, K.Y., Uddling, J., De Kauwe, M.G., 2022. Temperature responses of photosynthesis and respiration in evergreen trees from boreal to tropical latitudes. New Phytol. 234 (2), 353–374. https://doi.org/10.1111/nph.17951.

Davis, K.T., Peeler, J., Fargione, J., Haugo, R.D., Metlen, K.L., Robles, M.D., Woolley, T., 2024. Tamm review: a meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US. For. Ecol. Manag. 561, 121885. https://doi.org/10.1016/j.foreco.2024.121885.

del Campo, A.D., González-Sanchis, M., García-Prats, A., Ceacero, C.J., Lull, C., 2019. The impact of adaptive forest management on water fluxes and growth dynamics in a water-limited low-biomass oak coppice. Agric. For. Meteorol. 264, 266–282. https://doi.org/10.1016/j.agrformet.2018.10.016.

del Campo, A.D., Otsuki, K., Serengil, Y., Blanco, J.A., Yousefpour, R., Wei, X., 2022. A global synthesis on the effects of thinning on hydrological processes: implications for forest management. For. Ecol. Manag. 519, 120324. https://doi.org/10.1016/j.foreco.2022.120324.

Dix, M.J., Aubrey, D.P., 2021. Calibration approach and range of observed sap flow influences transpiration estimates from thermal dissipation sensors. Agric. For. Meteorol. 307, 108534. https://doi.org/10.1016/j.agrformet.2021.108534.

Ellis, E.C., Guy, R.D., Wei, X.A., 2024. Seasonal shifts in depth-to-water uptake by young thinned and overstocked lodgepole pine (*Pinus contorta*) forests under drought conditions in the Okanagan Valley, British Columbia, Canada. Hydrol. Earth Syst. Sci. 28 (20), 4667–4684. https://doi.org/10.5194/hess-28-4667-2024.

Fischer, E.M., Sippel, S., Knutti, R., 2021. Increasing probability of record-shattering climate extremes. Nat. Clim. Change 11 (8), 689–695. https://doi.org/10.1038/s41558-021-01092-9.

Flo, V., Martinez-Vilalta, J., Steppe, K., Schuldt, B., Poyatos, R., 2019. A synthesis of bias and uncertainty in sap flow methods. Agric. For. Meteorol. 271, 362–374. https://doi.org/10.1016/j.agrformet.2019.03.012.

Gebhardt, T., Häberle, K.-H., Matyssek, R., Schulz, C., Ammer, C., 2014. The more, the better? Water relations of Norway spruce stands after progressive thinning. Agric. For. Meteorol. 197, 235–243. https://doi.org/10.1016/j.agrformet.2014.05.013.

Gottardini, E., Cristofolini, F., Cristofori, A., Pollastrini, M., Camin, F., Ferretti, M., 2020. A multi-proxy approach reveals common and species-specific features associated with tree defoliation in broadleaved species. For. Ecol. Manag. 467, 118151. https://doi.org/10.1016/j.foreco.2020.118151.

Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T.W., Sperry, J.S., McDowell, N.G., 2020. Plant responses to rising vapor pressure deficit. New Phytol. 226 (6), 1550–1566. https://doi.org/10.1111/nph.16485.

Guttman, N.B., 1999. Accepting the standardized precipittaion index: a calculation algorithm. J. Am. Water Resour. Assoc. 35 (2), 311–322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x.

IPCC, 2023. Climate Change 2023: synthesis report. In: Lee, H., Romero, J. (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Jeong, D.I., Yu, B., Cannon, A.J., 2024. 2021 Heatwave over western North America: structural uncertainty and internal variability in GCM projections of Humidex and temperature extremes. Earths Future 12 (8), e2024EF004541. https://doi.org/10.1029/2024EF004541.

Kellomäki, S., Strandman, H., Kirsikka-Aho, S., Kirschbaum, M.U.F., Peltola, H., 2023. Effects of thinning intensity and rotation length on albedo- and carbon stock-based radiative forcing in boreal Norway spruce stands. Forestry 96 (4), 518–529. https://doi.org/10.1093/forestry/cpac058.

Khan, M.M.H., Muhammad, N.S., El-Shafie, A., 2020. Wavelet based hybrid ANN-ARIMA models for meteorological drought forecasting. J. Hydrol. 590, 125380. https://doi.org/10.1016/j.jhydrol.2020.125380.

Larcher, W., 2003. Physiological Plant Ecology: Ecophysiology and Stress Physiology of Functional Groups, fourth ed. Springer Science & Business Media, Berlin.

Li, J., Tam, C.-Y., Tai, A.P.K., Lau, N.-C., 2021. Vegetation-heatwave correlations and contrasting energy exchange responses of different vegetation types to summer heatwaves in the Northern Hemisphere during the 1982–2011 period. Agric. For. Meteorol. 296, 108208. https://doi.org/10.1016/j.agrformet.2020.108208.

Li, J., Yu, P., Wan, Y., Wang, Y., Yu, Y., Liu, B., Pan, L., Xu, L., Liu, Z., Wang, X., 2023. The differential responses of tree transpiration to seasonal drought among competitive pressures in a larch plantation of northwest China. Agric. For. Meteorol. 336, 109468. https://doi.org/10.1016/j.agrformet.2023.109468.

Lloyd, D., Angove, K., Hope, G.D., Thompson, C., 1990. A Guide to Site Identification and Interpretation for the Kamloops Forest Region. British Columbia Ministry of Forests, Research Branch.

López, R., Ramírez-Valiente, J.A., Pita, P., 2022. How plants cope with heatwaves in a drier environment. Flora 295, 152148. https://doi.org/10.1016/j.flora.2022.152148.

Mann, H.B., Whitney, D.R., 1947. On a test of whether one of two random variables is stochastically larger than the other. Ann. Math. Stat. 18 (1), 50–60. https://doi.org/10.1214/aoms/1177730491.

Maraun, D., Schiemann, R., Ossó, A., Jury, M., 2025. Changes in event soil moisture-temperature coupling can intensify very extreme heat beyond expectations. Nat. Commun. 16, 734. https://doi.org/10.1038/s41467-025-56109-0.

McKinnon, K.A., Simpson, I.R., 2022. How unexpected was the 2021 Pacific Northwest heatwave? Geophys. Res. Lett. 49 (18), e2022GL100380. https://doi.org/10.1029/2022GL100380.

Moore, R.D., Allen, D., MacKenzie, L., Spittlehouse, D., Winkler, R., 2021. Data sets for the Upper Penticton Creek watershed experiment: a paired-catchment study to support investigations of watershed response to forest dynamics and climatic variability in an inland snow-dominated region. Hydrol. Process. 35 (10), e14391. https://doi.org/10.1002/hyp.14391.

Parra, A., Greenberg, J., 2024. Climate-limited vegetation change in the conterminous United States of America. Glob. Change Biol. 30 (2), e17204. https://doi.org/10.1111/gcb.17204.

Preece, C., Verbruggen, E., Liu, L., Weedon, J.T., Peñuelas, J., 2019. Effects of past and current drought on the composition and diversity of soil microbial communities. Soil Biol. Biochem. 131, 28–39. https://doi.org/10.1016/j.soilbio.2018.12.022.

Rohner, B., Kumar, S., Liechti, K., Gessler, A., Ferretti, M., 2021. Tree vitality indicators revealed a rapid response of beech forests to the 2018 drought. Ecol. Indic. 120, 106903. https://doi.org/10.1016/j.ecolind.2020.106903.

Salomón, R.L., Peters, R.L., Zweifel, R., Sass-Klaassen, U.G.W., Stegehuis, A.I., Smiljanic, M., Poyatos, R., Babst, F., Cienciala, E., Fonti, P., Lerink, B.J.W., Lindner, M., Martinez-Vilalta, J., Mencuccini, M., Nabuurs, G.-J., van der Maaten, E., von Arx, G., Bär, A., Akhmetzyanov, L., Balanzategui, D., Bellan, M., Bendix, J., Berveiller, D., Blaženec, M., Čada, V., Carraro, V., Cecchini, S., Chan, T., Conedera, M., Delpierre, N., Delzon, S., Ditmarová, Ľ., Dolezal, J., Dufrêne, E., Edvardsson, J., Ehekircher, S., Forner, A., Frouz, J., Ganthaler, A., Gryc, V., Güney, A., Heinrich, I., Hentschel, R., Janda, P., Ježík, M., Kahle, H.-P., Knüsel, S., Krejza, J., Kuberski, Ł., Kučera, J., Lebourgeois, F., Mikoláš, M., Matula, R., Mayr, S., Oberhuber, W., Obojes, N., Osborne, B., Paljakka, T., Plichta, R., Rabbel, I., Rathgeber, C.B.K., Salmon, Y., Saunders, M., Scharnweber, T., Sitková, Z., Stangler, D.F., Stereńczak, K., Stojanović, M., Střelcová, K., Světlík, J., Svoboda, M., Tobin, B., Trotsiuk, V., Urban, J., Valladares, F., Vavrčík, H., Vejpustková, M., Walthert, L., Wilmking, M., Zin, E., Zou, J., Steppe, K., 2022. The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests. Nat. Commun. 13 (1), 28. https://doi.org/10.1038/s41467-021-27579-9.

Scharnweber, T., Smiljanic, M., Cruz-García, R., Manthey, M., Wilmking, M., 2020. Tree growth at the end of the 21st century - the extreme years 2018/19 as template for future growth conditions. Environ. Res. Lett. 15 (7), 074022. https://doi.org/10.1088/1748-9326/ab865d.

Schumacher, D.L., Hauser, M., Seneviratne, S.I., 2022. Drivers and mechanisms of the 2021 Pacific Northwest heatwave. Earths Future 10 (12), e2022EF002967. https://doi.org/10.1029/2022EF002967.

Shao, X., Zhang, Y., Ma, N., Zhang, X., Tian, J., Xu, Z., Liu, C., 2024. Drought-induced ecosystem resistance and recovery observed at 118 flux tower stations across the globe. Agric. For. Meteorol. 356, 110170. https://doi.org/10.1016/j.agrformet.2024.110170.

Shi, H., Zhao, Y., Liu, S., Cai, H., Zhou, Z., 2022. A new perspective on drought propagation: causality. Geophys. Res. Lett. 49 (2), e2021GL096758. https://doi.org/10.1029/2021GL096758.

Shi, L., Liu, H., Xu, C., Liang, B., Cao, J., Cressey, E.L., Quine, T.A., Zhou, M., Zhao, P., 2021. Decoupled heatwave-tree growth in large forest patches of *Larix sibirica* in northern Mongolian Plateau. Agric. For. Meteorol. 311, 108667. https://doi.org/10.1016/j.agrformet.2021.108667.

Skubel, R.A., Khomik, M., Brodeur, J.J., Thorne, R., Arain, M.A., 2017. Short-term selective thinning effects on hydraulic functionality of a temperate pine forest in eastern Canada. Ecohydrology 10 (1), e1780. https://doi.org/10.1002/eco.1780.

Slater, L., Coxon, G., Brunner, M., McMillan, H., Yu, L., Zheng, Y., Khouakhi, A., Moulds, S., Berghuijs, W., 2024. Spatial sensitivity of river flooding to changes in climate and land cover through explainable AI. Earths Future 12 (5), e2023EF004035. https://doi.org/10.1029/2023EF004035.

Sohn, J.A., Saha, S., Bauhus, J., 2016. Potential of forest thinning to mitigate drought stress: a meta-analysis. For. Ecol. Manag. 380, 261–273. https://doi.org/10.1016/j.foreco.2016.07.046.

Steppe, K., De Pauw, D.J.W., Doody, T.M., Teskey, R.O., 2010. A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. Agric. For. Meteorol. 150 (7), 1046–1056. https://doi.org/10.1016/j.agrformet.2010.04.004.

Stojanovic, M., Szatniewska, J., Kyselova, I., Pokorny, R., Cater, M., 2017. Transpiration and water potential of young *Quercus petraea* (M.) Liebl. coppice sprouts and seedlings during favourable and drought conditions. J. For. Sci. 63 (7), 313–323.

Tian, L., Yuan, S., Quiring, S.M., 2018. Evaluation of six indices for monitoring agricultural drought in the south-central United States. Agric. For. Meteorol. 249, 107–119. https://doi.org/10.1016/j.agrformet.2017.11.024.

Vose, J.M., Sun, G., Ford, C.R., Bredemeier, M., Otsuki, K., Wei, X., Zhang, Z., Zhang, L., 2011. Forest ecohydrological research in the 21st century: what are the critical needs? Ecohydrology 4 (2), 146–158. https://doi.org/10.1002/eco.193.

Wang, F., Mu, X., Hessel, R., Zhang, W., Ritsema, C.J., Li, R., 2013. Runoff and sediment load of the Yan River, China: changes over the last 60 yr. Hydrol. Earth Syst. Sci. 17 (7), 2515–2527. https://doi.org/10.5194/hess-17-2515-2013.

Wang, Y., Del Campo, A.D., Wei, X., Winkler, R., Liu, W., Li, Q., 2020. Responses of forest carbon and water coupling to thinning treatments from leaf to stand scales in a young montane pine forest. Carbon Bal. Manag. 15 (1), 24. https://doi.org/10.1186/s13021-020-00159-y.

Wang, Y., Wei, X., del Campo, A.D., Winkler, R., Wu, J., Li, Q., Liu, W., 2019. Juvenile thinning can effectively mitigate the effects of drought on tree growth and water consumption in a young *Pinus contorta* stand in the interior of British Columbia, Canada. For. Ecol. Manag. 454, 117667. https://doi.org/10.1016/j.foreco.2019.117667.

White, R.H., Anderson, S., Booth, J.F., Braich, G., Draeger, C., Fei, C., Harley, C.D.G., Henderson, S.B., Jakob, M., Lau, C.-A., Mareshet Admasu, L., Narinesingh, V., Rodell, C., Roocroft, E., Weinberger, K.R., West, G., 2023. The unprecedented Pacific Northwest heatwave of June 2021. Nat. Commun. 14 (1), 727. https://doi.org/10.1038/s41467-023-36289-3.

Winkler, R.D., Allen, D.M., Giles, T.R., Heise, B.A., Moore, R.D., Redding, T.E., Spittlehouse, D.L., Wei, X., 2021. Approaching four decades of forest watershed research at Upper Penticton Creek, British Columbia: a synthesis. Hydrol. Process. 35 (5), e14123. https://doi.org/10.1002/hyp.14123.

Xu, Z., Man, X., Hou, Y., Shang, Y., Cai, T., 2023. Canopy transpiration and its controlling mechanisms among rainfall patterns in a boreal larch forest in China. J. Hydrol. 625, 130041. https://doi.org/10.1016/j.jhydrol.2023.130041.

Yang, H., Munson, S.M., Huntingford, C., Carvalhais, N., Knapp, A.K., Li, X., Peñuelas, J., Zscheischler, J., Chen, A., 2023a. The detection and attribution of extreme reductions in vegetation growth across the global land surface. Glob. Change Biol. 29 (8), 2351–2362. https://doi.org/10.1111/gcb.16595.

Yang, H., Tao, W., Ma, Q., Xu, H., Chen, L., Dong, H., Yang, Y., Smith, N.G., Chen, L., 2023b. Compound hot extremes exacerbate forest growth decline in dry areas but not in humid areas in the Northern Hemisphere. Agric. For. Meteorol. 341, 109663. https://doi.org/10.1016/j.agrformet.2023.109663.

Yang, L., Wang, J., Geng, Y., Niu, S., Tian, D., Yan, T., Liu, W., Pan, J., Zhao, X., Zhang, C., 2022. Heavy thinning reduces soil organic carbon: evidence from a 9-year thinning experiment in a pine plantation. Catena 211, 106013. https://doi.org/10.1016/j.catena.2021.106013.

Yao, Y., Liu, Y., Zhou, S., Song, J., Fu, B., 2023. Soil moisture determines the recovery time of ecosystems from drought. Glob. Change Biol. 29 (13), 3562–3574. https://doi.org/10.1111/gcb.16620.

Yin, D., Gou, X., Liu, J., Zhang, D., Wang, K., Yang, H., 2024. Increasing deep soil water uptake during drought does not indicate higher drought resistance. J. Hydrol. 630, 130694. https://doi.org/10.1016/j.jhydrol.2024.130694.

Yin, J., Gentine, P., Slater, L., Gu, L., Pokhrel, Y., Hanasaki, N., Guo, S., Xiong, L., Schlenker, W., 2023. Future socio-ecosystem productivity threatened by compound drought–heatwave events. Nat. Sustain. 6 (3), 259–272. https://doi.org/10.1038/s41893-022-01024-1.

Zhang, H., Liu, S., Yu, J., Li, J., Shangguan, Z., Deng, L., 2024. Thinning increases forest ecosystem carbon stocks. For. Ecol. Manag. 555, 121702. https://doi.org/10.1016/j.foreco.2024.121702.

Zhang, M., Wei, X., Li, Q., 2016. A quantitative assessment on the response of flow regimes to cumulative forest disturbances in large snow-dominated watersheds in the interior of British Columbia, Canada. Ecohydrology 9 (5), 843–859. https://doi.org/10.1002/eco.1687.

Zhang, X., Chen, L., Wang, Y., Jiang, P., Hu, Y., Ouyang, S., Wu, H., Lei, P., Kuzyakov, Y., Xiang, W., 2023. Plantations thinning: a meta-analysis of consequences for soil properties and microbial functions. Sci. Total Environ. 877, 162894. https://doi.org/10.1016/j.scitotenv.2023.162894.

Zhang, X., Zheng, F., Zhu, J., Chen, X., 2022. Observed frequent occurrences of marine heatwaves in most ocean regions during the last two decades. Adv. Atmos. Sci. 39, 1579–1587. https://doi.org/10.1007/s00376-022-1291-3.

Zhang, X., Guan, D., Li, W., Sun, D., Jin, C., Yuan, F., Wang, A., Wu, J., 2018. The effects of forest thinning on soil carbon stocks and dynamics: a meta-analysis. For. Ecol. Manag. 429, 36–43. https://doi.org/10.1016/j.foreco.2018.06.027.

Zhou, T., Wang, C., Zhou, Z., 2020. Impacts of forest thinning on soil microbial community structure and extracellular enzyme activities: a global meta-analysis. Soil Biol. Biochem. 149, 107915. https://doi.org/10.1016/j.soilbio.2020.107915.
Zhou, Z., Wang, C., Jin, Y., Sun, Z., 2019. Impacts of thinning on soil carbon and nutrients and related extracellular enzymes in a larch plantation. For. Ecol. Manag. 450, 117523. https://doi.org/10.1016/j.foreco.2019.117523.
Zscheischler, J., Westra, S., van den Hurk, B.J.J.M., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Change 8 (6), 469–477. https://doi.org/10.1038/s41558-018-0156-3.