

Article

Drought Impact on Eco-Physiological Responses and Growth Performance of Healthy and Declining *Pinus sylvestris* L. Trees Growing in a Dry Area of Southern Poland

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Abstract: In recent years, several drought events hit Poland, affecting its forests. In Opole, Poland, tons of *Pinus sylvestris* L. deadwood is removed every year due to drought. Understanding the physiological mechanisms underlying tree vulnerability to drought, and tree responses, is important to develop forest management strategies to face the ongoing climate change. This research provides comprehensive local-scale analyses of the sensitivity of healthy and declining trees to drought. We used dendrochronology and stable isotope analysis to compare five healthy and five declining trees. The analysis focused particularly on comparisons of basal area increment (BAI), $\delta^{13}\text{C}$, and intrinsic water-use efficiency (iWUE), as well as tree resistance, resilience, and recovery in response to drought events and sensitivity to selected meteorological parameters. We observed a significant reduction in BAI values in declining trees after 2000. Fifteen years later, the reduction was also visible in the iWUE values of these trees. Despite similar $\delta^{13}\text{C}$ chronology patterns, declining trees showed higher $\delta^{13}\text{C}$ correlations with meteorological parameters. We have shown that dendrochronology enables early detection of poor forest health conditions. Differences in iWUE chronologies occurring in recent years suggest that trees of both groups have chosen different adaptive strategies to cope with drought stress.

Keywords: declining trees; intrinsic water-use efficiency; carbon isotopes; drought; *Pinus sylvestris* L.; Poland



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1. Introduction

Global warming is a serious problem for forest ecosystems since the gradual increase in average temperatures is threatening forest health and its ecosystem services. According to the Intergovernmental Panel on Climate Change (IPCC) assessment report [1], 2011–2020 was considered the warmest decade in world history. During this period, Poland recorded an average of 13 days a year with a minimum temperature of 30 °C, while in the 1970s, it was only 4 days. One of the effects of global warming is an increase in the frequency and intensity of extreme weather phenomena, such as droughts [2]. The drought events have contributed to tree mortality in Europe [1]; particularly, in Poland, drought-related tree mortality doubled from 1984 to 2016 [3]. Higher frequencies of droughts not only lead to the death of trees but also increase their susceptibility to pests [4] and thus lead to the need to cut down large forest areas every year [5,6]. Some trees are more affected by drought than others, and even trees of the same species growing in the same area can respond differently to water shortage [7,8]. It is unclear what structural modifications and physiological and ecological

mechanisms underlie the processes of tree dieback due to drought [9,10]. There is still great uncertainty about how forests will respond to further changes, so further research on trees' sensitivity to drought is necessary to better understand this problem.

Eco-physiological mechanisms behind drought-induced tree mortality linked to the carbon and water economy have been evaluated in numerous research works [11–13]. The ability of trees to control water loss is crucial to their survival [11]. Trees can close their stomata to reduce water loss and resist severe drought conditions by preventing hydraulic dysfunctions. However, if stomatal closure persists, it may trigger a mechanism known as carbon starvation, which is detrimental to their health as well [13,14]: stomatal closure impairs the uptake of CO₂, reducing photosynthesis. In the long term, this phenomenon reduces the carbohydrate pool available to the plant [15], threatening crucial physiological and ecological processes like biomass maintenance, growth, and reproduction [16–18]. Another mechanism leading to the death of trees is xylem hydraulic failure; according to many studies, a broad reduction in xylem conductivity causes tree mortality well before carbon starvation becomes deadly [13,19,20]. Although *Pinus sylvestris* L. is considered a drought-resistant species, recent studies carried out in southern and central Europe [21–23], and particularly in Poland [24,25], reported several episodes of drought-induced dieback in Scots pine.

One of the tools for examining the sensitivity of trees to drought is dendrochronology [26,27]. In forest stands under environmental stress, tree rings have often been used as indicators of tree vitality [28,29]. The formation of annual growth rings is a consequence of the micro/macroenvironmental conditions in which trees live [28]. Therefore, the reconstruction of stressful climatic events is possible with the use of tree rings. Analyzing the effects of disturbance events on ecological parameters is a common method used to determine the resilience and resistance of the ecosystems under study. Various approaches comparing disturbed and undisturbed ecosystems can be found in the literature [30–32]. In dendrochronological studies, the resilience, resistance, and recovery indices can be computed from the growth time series [33], and in recent years, it has become an established procedure [33,34]. Most often, for this kind of analysis, the BAI time series is employed [34].

Dendrochronology is often combined with the stable isotope analysis of tree rings, which provides more accurate insights into trees' sensitivity to drought stress [7,28]. In effect, tree-ring stable isotopes can be used to reconstruct the effects of environmental disturbances on tree growth and vitality [28]. Changes in atmospheric CO₂ concentrations (c_a) and substomatal chamber or intercellular CO₂ concentrations (c_i) both have an impact on the carbon isotope ratio (δ¹³C) [28]. The stomata control the substomatal chamber's CO₂ input rate (g_s), while CO₂ assimilation (A) controls the output rate [28]. Environmental factors including light, temperature, and the availability of water and nutrients have a significant impact on these processes, and tree-ring stable isotopes reflect this influence [28]. Under stress conditions, like a water deficit, ¹³C discrimination decreases, which could be explained by partial or total stomatal closure during the water stress event, which results in reduced carbon isotope discrimination due to limited CO₂ and H₂O diffusion [35]. Furthermore, tree-ring δ¹³C has been frequently used to infer intrinsic water use efficiency in plants (iWUE) due to its link with the ratio between the intercellular and ambient CO₂ partial pressures [36,37].

In the literature, several studies have considered the approaches mentioned above to explore tree sensitivity to drought in different conditions, both on a regional [38] and global scale [39,40], and comparing different tree species [26]. Colangelo et al. [41] conducted research on declining and nondeclining trees in two forests in Italy. The authors showed that growth data can provide early warning signals to forecast tree dieback [41]. Particularly, in the most drought-affected site, the authors noted that declining trees showed a decreased iWUE following the onset of dieback, which suggested an increased water loss [41]. Timofeeva et al. [7] studied *Pinus sylvestris* L. in various health conditions growing in one of the driest parts of the European Alps, which were subjected to a 10-year irrigation experiment. The authors observed that irrigated trees showed a continuous rise in growth

and an immediate decrease in $\delta^{13}\text{C}$ values, suggesting increased stomatal conductance and proving that water is a major growth-limiting factor [7]. Genetic differences may play a significant role in assessing phenomena such as drought-induced forest die-off [41–43]. Lloret and Garcia [42] examined the contribution of ecological, morphological, and genetic factors to the understanding of how trees react to extended drought. The authors conducted some empirical studies confirming the relationship between the response to drought stress at the individual level and the genetic background [42]. However, it was also shown that there is no relationship between plant performance and the average genetic relatedness between individuals in a plot [42]. The literature also provides examples of other factors operating at the microlocal or local scale that may cause differences in the response of trees to drought [44–46]. Galiano [44], based on the patchy damage pattern observed in their study area, suggests that microtopography, soil properties, and stand structure possibly related to prior management had an impact on predisposing trees to greater susceptibility to climatic drought. The sensitivity of individual *Pinus sylvestris* trees to drought is highly variable, even within groups of individuals with the same provenance [47]. In recent years, research aimed at providing a mechanistic or physiological explanation of this variability is gaining increased attention [48], as the problems related to climate change are becoming increasingly pressing.

Despite the presence of several studies in the literature, research on tree sensitivity to drought on a local scale is still scarce. Furthering this knowledge would enable an understanding of the drought responses of nearby trees, thus contributing to a better understanding of the mechanism underlying their decline. In this context, the aim of this research is to conduct a comparative analysis of trees experiencing drought, growing in the same area (at a distance of 0.5 m to 500 m between individual trees), but in different states of health: healthy and declining. We used dendrochronology coupled with measurements of stable carbon isotopes in tree rings to monitor growth trends and water-use dynamics of *Pinus sylvestris*, a species widely distributed in Poland and threatened by ongoing global warming. Our hypothesis is that despite similar growth conditions, nearby trees may show signs of dieback. We expect declining trees may exhibit early warning signals, such as reduced growth patterns, changes in water-use efficiency, and increased sensitivity to the meteorological parameters compared with healthy trees.

2. Materials and Methods

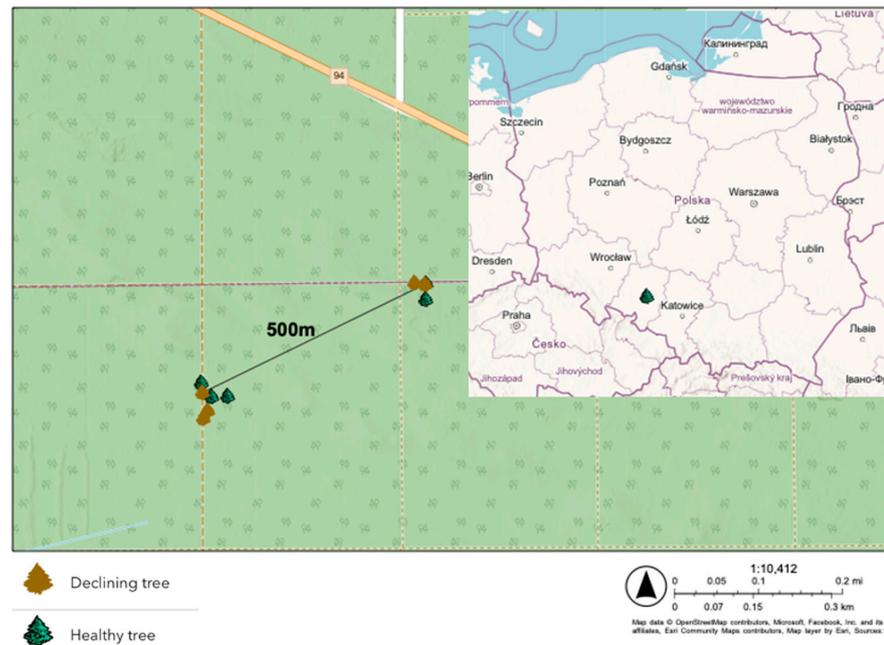
2.1. Study Area

The study region is situated in southern Poland's Opole Forest District (50°37'19.8" N 18°02'20.8" E) (Figure 1a). The Forest District is 22,867.87 hectares in size, with 86% of that being made up of pine trees. The remaining areas are made up of 5% oaks, 4% birch, 3% alders, and 2% other species [49]. As reported by Lasy Państwowe [49], the majority of pine trees (57.2%) in Opole forests are between 50 and 100 years old. The lowland, periglacial, plain, and undulating environment of the sampling location is typified by gravel-type and sand-dominated soils [49].

Several drought definitions exist [50]; in our study, we chose the SPEI index for individuating droughty years. This is because SPEI is representative of the water availability to vegetation and has been widely used in forest research [6,51,52]. More specifically, we considered severely droughty years: all the years where the SPEI value was below 1.5 [53]. Opole's forestry departments have been dealing with a major issue in recent years: an enormous number of pines (*Pinus sylvestris* L.) are dying each year as a result of drought events. Pine trees growing in Opole forests have been accustomed to growing in partially wet areas with high groundwater levels. As a result, the trees developed shallow root systems. A drought lasting several weeks in the summer of 2015 resulted in a decrease in the groundwater level and, as a result, cut off the pine trees from access to water. According to the study by Zespół Ochrony Lasu w Opolu [54], the amount of cut deadwood increased 17 times after the drought in 2015 compared with prior years. Prolonged low rainfall and high temperatures led to reduced pines' resistance. The trees' demise was accelerated

by their increased susceptibility to mistletoe and bark beetle assaults [54]. At the nearby meteorological station, maximum growing-season temperatures have gradually increased over the past 20 years (by 1.3 °C relative to prior years). In the Opole Forest district, the problem of large-scale stand dieback, caused by drought, is much more serious than in other forests of southern Poland [55]. For that reason, the chosen site is a good one to study drought impact on *Pinus sylvestris* L. trees in various health conditions.

(a)



(b)

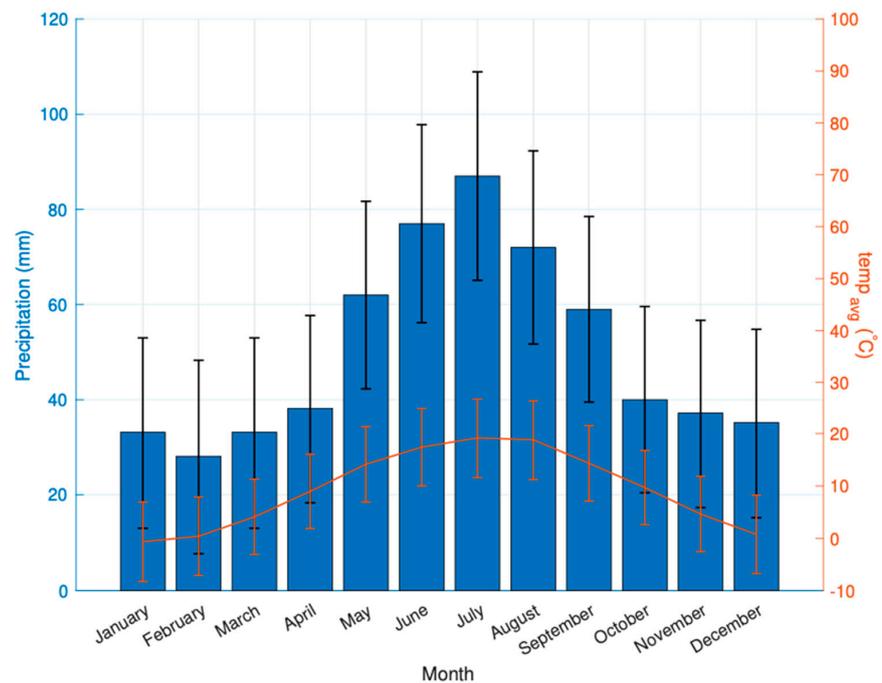


Figure 1. (a) Location of the sampled trees in Opole and Poland and scale; (b) the average monthly sum of precipitation (blue bars) and average temperature (red line) at the meteorological station in Opole; the error bars show the standard deviation. Reference period 1975–2022.

The *Pinus sylvestris* L. species, commonly known as Scots Pine, is widespread throughout Europe, and its growth phenology varies based on latitude. In fact, the phenological cycle of the species is strongly influenced by environmental factors, such as temperature and water availability. Therefore, Scots Pine can thrive in various climatic conditions, extending or shortening its growing season. In previous studies conducted in Central Europe, the onset of cambial activity was often observed around April and lasted until autumn [56].

Monthly data on average and maximum temperatures, total monthly precipitation, and relative humidity were acquired for the examined period (1975–2022) from the “Opole” meteorological station (50°37′37″ N, 17°58′08″ E) (Figure 1a,b), which is the closest one to the sampling site (6 km). The information came from the Polish Institute of Meteorology and Water Management (IMGW-PIB) [57]. On the Opole meteorological station, the lowest temperatures are recorded in January, while the highest are in July (Figure 1b). The Standardized Precipitation–Evapotranspiration Index (SPEI-3) data at a monthly time resolution, with a 3-month backward accumulation window, were sourced from SPEIbase v.2.9 [58], and hereafter, we refer to them as “SPEI” for simplicity.

2.2. Dendrochronological Analyses

The sampling was performed in November 2022: wood cores were taken at a height of 1.3 m from the ground. From each tree, four wood cores were extracted in four different directions in space reaching the pith using a 5 mm increment borer (Haglöfs, Långsele, Sweden). Five declining trees were selected from among those marked to be fallen by foresters, based on visible signs of poor health: the presence of scant needles, poor, not plentiful crowns, and the presence of mistletoe. As a control, another 5 trees without any sign of decline were selected and sampled. Previous research confirms the effectiveness of using this number of trees in similar analyses [59,60]. Every sample was adhered to wooden stands and sanded with sandpaper of several grits (P60, P220, P400, P600) in order to improve the visibility of the annual rings. The samples processed in this way were examined using the LINTAB system, which consists of a stereo microscope connected to a computer, which records the measures of ring width with the TSAP-Win software version 0.3. The consistency of trends between several TRW series was assessed using the Gleichlaufigkeit (GLK) index [61]. The results were considered valid when they satisfied the criterion of having a GLK value higher than 60 [62]. The dplR package in RStudio [63] was used for cross-dating tree rings: the program calculated TRW correlation coefficients between a given sample and residual samples from different trees. To validate the consistency of the TRW series among trees from the same location, cross-dating quality was checked using COFECHA [64]. The bai.in function in the dplR package was used to compute BAI data [63].

2.3. Resistance, Resilience, and Recovery Indices

We estimated multiple interrelated but complementary indices to address tree health status, and in particular resistance, resilience, and recovery based on variations in tree ring width according to Lloret et al. [65]. For the computation, we assumed as reference the 5-year period preceding each drought event (identified using the low August SPEI) and used BAI as the growth indicator. The resistance index (R_t) was calculated as the ratio of growth during the drought to the growth observed in the predrought period. The resilience index (R_s) was assessed as the ratio of growth in the period after the drought to the growth in the period before the stress event. The recovery index (R_c) was obtained from the ratio of the average growth in the 5-year period after the drought and during the drought.

2.4. Isotopes Analysis and *i*WUE

After dendrochronological analysis, all samples were analyzed in a mass spectrometer to determine their carbon isotopic composition. We divided the samples into two groups: healthy trees and declining trees. Within each group, we analyzed mixed material from all

trees. Due to the very small width of some increments (especially in the last 20 years), it was not possible to divide the samples into individual tree rings; therefore, each sample was divided into 3-year increments, starting from 1975–1977 and ending with 2020–2022. Whole wood samples were cut into small pieces and placed in tin capsules in an amount of 70–100 μg and then analyzed in IsoPrime mass spectrometer coupled with the EuroVector elemental analyzer to assess $\delta^{13}\text{C}$. Using the $\delta^{13}\text{C}$ values of the divided tree ring, we estimated iWUE ($\mu\text{mol CO}_2 \times \text{mol H}_2\text{O}^{-1}$), which is defined as the ratio between photosynthesis rate (A) and its stomatal conductance (g), based on the following equation:

$$\text{iWUE} = \frac{(c_a - c_i)}{1.6} = \frac{A}{g}, \quad (1)$$

where c_a is the concentration of CO_2 in the atmosphere (estimated values are obtained from McCarroll, D.; Loader, N.J. [66]), c_i is the concentration of CO_2 inside cells, and 1.6 is the ratio of diffusivities of water and CO_2 in the atmosphere. The following equation was used to determine the c_i value:

$$c_i = c_a \left(\delta^{13}\text{C}_{\text{tree}} - \delta^{13}\text{C}_{\text{air}} + a \right) / (b - a), \quad (2)$$

where a is the fractionation factor due to CO_2 diffusion through stomata ($a = -4.4$), and b is the fractionation factor due to Rubisco enzyme during photosynthesis ($b = 27$) [66]. The tree-ring data were corrected to remove atmospheric decline in $\delta^{13}\text{C}$, using the method proposed by McCarroll, D.; Loader, N.J. [66]. This correction was necessary because, since industrialization, the $\delta^{13}\text{C}$ value of air has dropped by about 1.5‰, as burned coal and oil are depleted in ^{13}C [66].

Plotting of $\delta^{13}\text{C}$ records was performed with the dplR package [63]. Relationships between average temperature, maximum temperature, precipitation, humidity, SPEI, and $\delta^{13}\text{C}$ were examined using the treeclim package [67]. In this package, correlations are estimated using Pearson's linear correlation coefficient. Analyses were performed for the years 1975–2022, with the dendroclimatic window being set from May of the previous year to October of the current year. A 95% significance level ($p < 0.05$) was used to compute the static correlations. The differences between healthy and declining trees were examined using the two-tailed distribution of Student's t -test, with statistically significant values for $p < 0.05$ [68].

3. Results

3.1. Tree Growth Analysis

The BAI chronology for healthy trees was characterized by an increasing trend ($R^2 = 0.46$) (Figure 2a). In the case of declining trees, we did not observe a trend ($R^2 = 0.05$) (Figure 2a). The average BAI value for healthy trees was 2177 mm^2 , while for declining trees, this value was 25% lower, amounting to 1675 mm^2 . Until 2000, the chronologies of both groups were similar; we did not observe statistically significant differences ($p > 0.05$). After 2000, BAI values for declining trees were clearly lower, and we observed a significant difference ($p < 0.05$) between the two groups of trees (Figure 2a).

In years when the August SPEI value was the lowest ($\text{SPEI} < 1.5$), we also observed reduced BAI values in trees of both groups (Figure 2a,b). In five of the six particularly dry years (1983, 1992, 1999, 2003, 2015, 2018), BAI values for declining trees were less than or equal to those for healthy trees (Figure 2a,b). The negative impact of drought on tree growth is supported by the calculated resistance index (Rt) (Table 1). In 9 out of 12 cases, this index was in decline ($R_t < 1$), indicating a reduction in tree growth for both groups during drought compared with the years preceding the drought stress occurrence (Table 1). Of the six droughts considered, only two events (1983, 1999) did not affect the Rt index of the healthy trees. In the case of declining trees, only the drought of 1992 did not influence their Rt index (Table 1). The droughts of 2015 and 2018 also led to a decrease in the resistance index value ($R_s < 1$) for both groups of trees, suggesting a decline in the average BAI values

in the 5 years following the droughts (Table 1). Additionally, the droughts of 1999 and 2003 caused a decrease in the recovery index ($R_c < 1$) of declining trees, indicating a reduction in BAI over the 5 years following the drought event (Table 1). This effect was also observed in the case of healthy trees during the 2015 drought ($R_c < 1$) (Table 1).

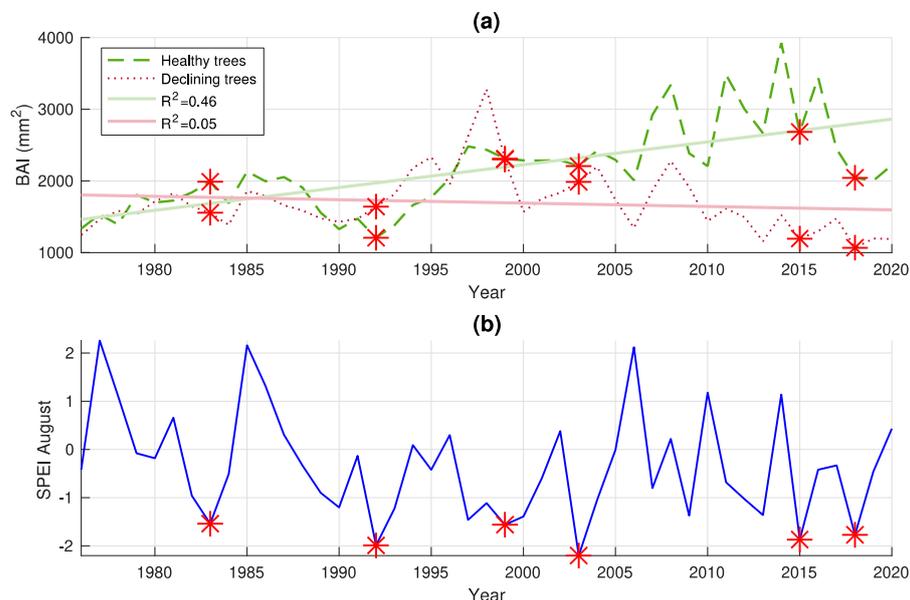


Figure 2. (a) Annual Basal Area Increment (BAI) for healthy and declining groups of trees with fitted trend lines. (b) Standardized Precipitation–Evapotranspiration Index (SPEI) data for August. The asterisk symbol indicates years (1983, 1992, 1999, 2003, 2015, 2018), with particularly low August SPEI (<1.5).

Table 1. Resistance, resilience, and recovery coefficients for healthy and declining trees in years with the lowest August SPEI (<1.5). Bold letters indicate values less than 1.

Group	Resistance Index (R_t)	Resilience Index (R_s)	Recovery Index (R_c)	Year with Lowest August SPEI
Healthy	1.18 (± 0.11)	1.16 (± 0.11)	0.98 (± 0.08)	1983
Declining	0.94 (± 0.06)	1.00 (± 0.13)	1.06 (± 0.10)	
Healthy	0.73 (± 0.12)	1.12 (± 0.23)	1.55 (± 0.13)	1992
Declining	1.08 (± 0.07)	1.43 (± 0.11)	1.33 (± 0.11)	
Healthy	1.11 (± 0.18)	1.11 (± 0.15)	0.99 (± 0.03)	1999
Declining	0.93 (± 0.19)	0.76 (± 0.32)	0.81 (± 0.16)	
Healthy	0.95 (± 0.02)	1.12 (± 0.16)	1.18 (± 0.16)	2003
Declining	0.93 (± 0.30)	0.88 (± 0.43)	0.95 (± 0.21)	
Healthy	0.88 (± 0.17)	0.80 (± 0.37)	0.91 (± 0.24)	2015
Declining	0.83 (± 0.10)	0.86 (± 0.20)	1.04 (± 0.12)	
Healthy	0.67 (± 0.12)	0.76 (± 0.27)	1.13 (± 0.09)	2018
Declining	0.80 (± 0.10)	0.87 (± 0.16)	1.08 (± 0.06)	

3.2. Isotope Analysis in Tree Rings

$\delta^{13}\text{C}$ chronologies for healthy and declining trees were characterized by similar patterns (Figure 3a); we did not observe significant differences between them ($p > 0.05$). The average $\delta^{13}\text{C}$ value for healthy trees was -23.71‰ , and for declining trees, it was -23.79‰ . Both chronologies showed an increasing trend: in the chronology of the healthy group of trees ($R^2 = 0.50$) (Figure 3a), there were several fluctuations that were absent in the chronology of the declining trees, for which the increasing trend was stronger ($R^2 = 0.85$)

(Figure 3a). In Figure 3b, the average trend of average temperatures during the growing season is reported: in years with higher average temperatures, $\delta^{13}\text{C}$ values of healthy trees increased.

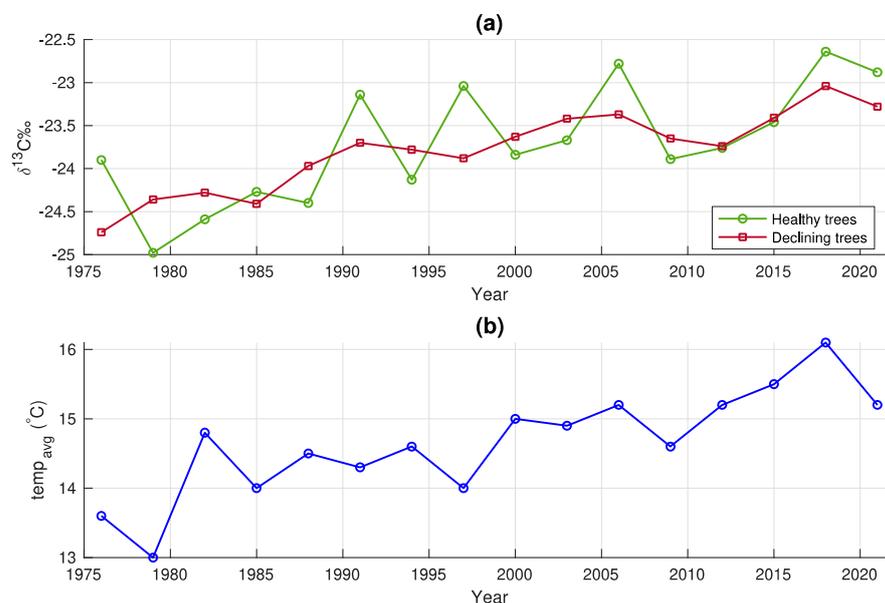


Figure 3. (a) $\delta^{13}\text{C}$ chronologies for healthy and declining trees, and (b) average values of average monthly temperatures during the growing season (April–October).

Healthy trees showed no significant correlations of $\delta^{13}\text{C}$ with humidity (Figure 4a). Precipitation at the beginning of the growing season in both the current and previous years influenced the $\delta^{13}\text{C}$ values of the healthy trees; we found three significant negative $\delta^{13}\text{C}$ -precipitation correlations (Figure 4a). In the case of SPEI, one statistically significant positive $\delta^{13}\text{C}$ -SPEI correlation occurred (June of the current year), which concerned healthy trees (Figure 4a). For this group of trees, we found one significant positive correlation for $\delta^{13}\text{C}$ with average temperature (June of the current year) and did not find any correlation with maximum temperature (Figure 4a). Declining trees were more sensitive to changes in humidity, precipitation, and SPEI. This is evidenced by the correlation coefficients between $\delta^{13}\text{C}$ and the indicated meteorological parameters, which were statistically significant ($p < 0.05$) for most of the considered months (Figure 4b). The parameter that had the greatest impact on the $\delta^{13}\text{C}$ values of declining trees was humidity; in 13 of the 18 months analyzed, the correlation coefficients were statistically significant (negative correlations, $p < 0.05$) (Figure 4b). For $\delta^{13}\text{C}$ -precipitation correlations, we also observed a high number of statistically significant correlations for declining trees that occurred in 10 months. Only correlations in the current year in April, and the previous November, were positive; the remaining correlations were negative (Figure 4b). Declining trees showed nine statistically significant $\delta^{13}\text{C}$ -SPEI correlations. Correlations in November of the previous year and March of the current year were positive, while the remaining correlations were negative (Figure 4b). Similarly to healthy trees, declining trees showed only one significant positive correlation between $\delta^{13}\text{C}$ and average temperature (current February) (Figure 4b). In the case of maximum temperature, we also observed one significant correlation for declining trees (negative correlation in November of the previous year).

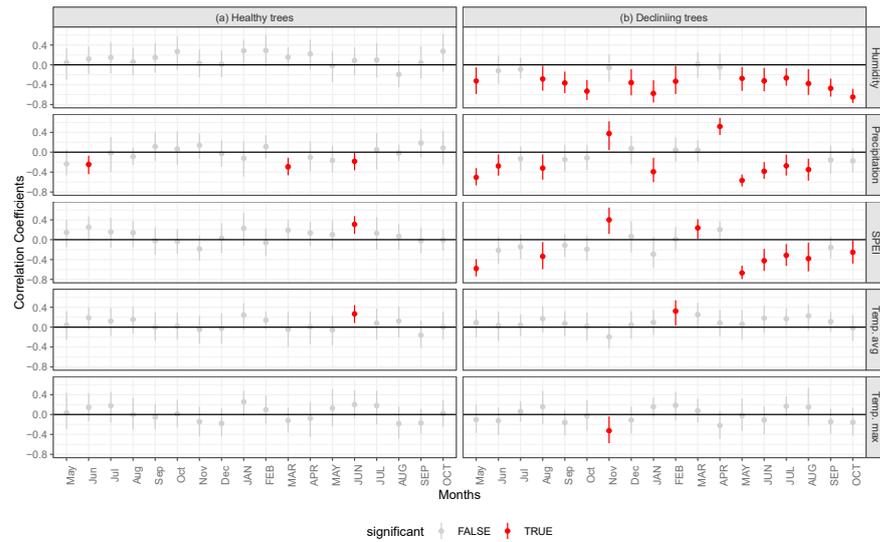


Figure 4. Correlation coefficients between $\delta^{13}\text{C}$ and meteorological parameters (relative humidity, precipitation, SPEI, maximum temperature, average temperature) for (a) healthy trees and (b) declining trees. Months in lowercase refer to the previous year, while months in capital refer to the current year. The correlation’s average is represented by the point, and its 95% confidence interval, derived from 1000 bootstrap samples, is shown by the error bar [67]. Red bars indicate a statistically significant correlation ($p < 0.05$).

The iWUE chronologies for healthy and declining trees showed similar patterns, and the values of the two groups did not differ significantly until 2015 (Figure 5a). After 2015, the iWUE of both groups increased, but the increase was significantly greater ($p < 0.05$) for healthy trees. A difference was observed between healthy and declining trees in terms of the relationship between iWUE and BAI (Figure 5b,c). In the case of healthy trees, the value of the coefficient of determination was higher ($R^2 = 0.42$, $p < 0.05$), while for declining trees it was close to zero ($R^2 = 0.09$, $p < 0.05$).

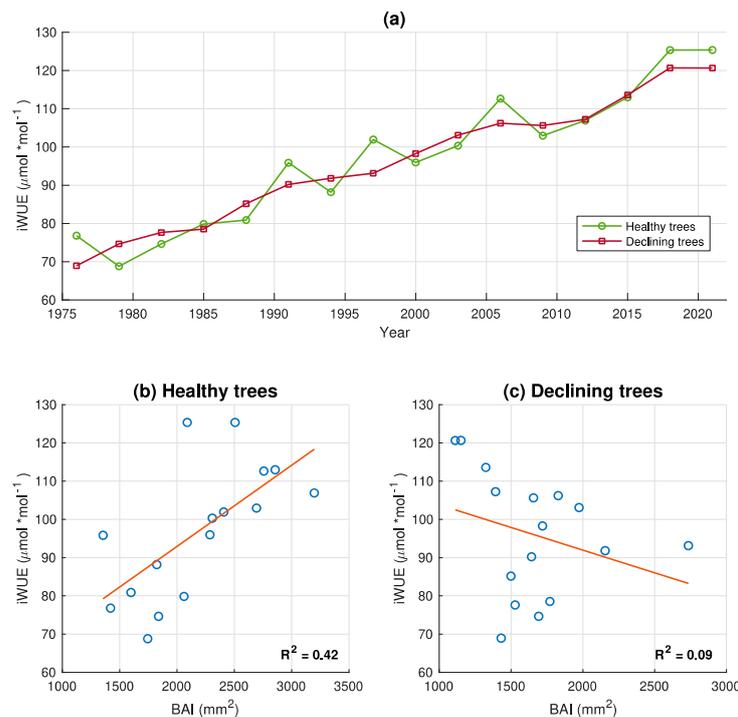


Figure 5. (a) iWUE chronologies for healthy and declining trees; (b) relationship between Basal Area Increments (BAI) and intrinsic water-use efficiency (iWUE) for healthy trees (c) and declining trees.

4. Discussion

In this study, we investigated the growth dynamics, eco-physiological responses, and intrinsic water-use efficiency of declining trees. The results of this study aim to fill the knowledge gap on the dynamics of decay of trees growing in close proximity but with different health statuses under identical climate conditions. The area selected for analysis falls within the Opole Forest District, which represents a significant critical region in Poland due to the substantial annual tree removal as a result of drought. This region also holds the record for the highest temperature ever recorded in Poland (40.2 °C).

Our results reveal distinct patterns in the BAI chronologies between the two groups, with declining trees displaying significantly lower radial growth post 2000. Droughts emerged as factors affecting both healthy and declining trees, with the latter showing greater sensitivity, marked by reduced BAI values. Carbon isotope discrimination ($\delta^{13}\text{C}$) patterns reflected differential sensitivities to environmental factors, with declining trees responding more significantly to changes in humidity, precipitation, and SPEI. Furthermore, the increasing trend in iWUE post 2015 highlighted a divergence between healthy and declining trees. Notably, the positive correlation between iWUE and BAI in healthy trees suggested an increase in photosynthetic rate with reduced water loss [69]. On the contrary, the lack of correlation between iWUE and BAI for declining trees could indicate the opposite, i.e., a greater water loss rather than carbon uptake [70].

The observed patterns in BAI chronologies provide valuable insights into the growth dynamics of healthy and declining trees in response to changing environmental conditions. Until the year 2000, both healthy and declining trees represented similar growth patterns. However, the difference appeared post 2000, with declining trees displaying significantly lower BAI values. The reduction in the BAI values in declining trees can be associated with the increased frequency of droughts in Poland over the last 10 years [71]. Foresters from the Opole Forest District began to observe a decline in trees in 2015 (after a severe drought); a decrease in BAI values in trees after 2000 may suggest that the decline process began earlier. The observed differences in growth patterns between healthy and declining trees are in line with findings from previous studies [72–74] that have reported compromised growth and productivity in trees under stress. Values of resilience, resistance, and recovery coefficients below 1 in years of reduced August SPEI for both groups of trees indicate a negative impact of drought on both declining and healthy trees [33]. The number of stress events resulting in a subsequent reduction in BAI (compared with previous years) was twice as high in the case of declining trees, which may suggest their greater sensitivity to unfavorable environmental conditions. There are many studies suggesting that low resilience to drought may actually increase the risk of mortality for the trees [75–77]. DeSoto et al. [39] analyzed over 3500 trees from 180 different sites and showed that trees that died due to drought were less resilient to droughts occurring decades before the event that led to their complete decline. We observed a similar pattern in our research. Declining trees showed lower resilience index (Rs) values than healthy trees during droughts (in 1983, 1999, 2003) preceding the beginning of their death, as indicated by foresters in 2015. Of the events preceding 2015, only in 1992 did we observe the opposite situation, where the resilience of healthy trees was lower than that of declining trees. However, for both groups of trees, the Rs index was greater than 1, indicating that this event may not have had a major impact on the trees. The differences within the sites in drought resilience between trees in various health states may be explained by differences in microenvironmental factors, such as intraplot heterogeneity and competition and soil properties (intrinsic) or in characteristics that dictate plant water and carbon economies (extrinsic) [11,78,79].

Although the $\delta^{13}\text{C}$ chronologies of both groups of trees had similar overall patterns, with $\delta^{13}\text{C}$ values increasing over time, there were notable differences in their sensitivity to specific climatic variables. Shestakova et al. [80] analyzed the sensitivity of pine trees (*Pinus sylvestris* L.) in European forests to changes in meteorological conditions. The $\delta^{13}\text{C}$ values of all analyzed trees exhibited a positive correlation with average temperatures in June [80]. Specifically, trees in Finland, Norway, and Spain demonstrated significant

($p < 0.05$) positive $\delta^{13}\text{C}$ –temperature correlations from June to August [80]. However, for trees in Poland, significant ($p < 0.05$) correlations were found only in June [80]. These findings align with our observations of $\delta^{13}\text{C}$ average temperature correlations for healthy trees. Also, in the case of precipitation, the responses of healthy trees analyzed by us were similar to the $\delta^{13}\text{C}$ –precipitation correlations obtained by Shestakova et al. [80] (significant negative correlation in June). This may indicate that healthy trees showed $\delta^{13}\text{C}$ responses to average temperature and precipitation typical for the *Pinus sylvestris* L. species in Polish climatic conditions. Hemming et al. [81] analyzed the relationship between climate parameters and the carbon stable isotope composition of various tree species, including *Pinus sylvestris* L. trees in Great Britain. The authors found significant ($p < 0.05$) negative $\delta^{13}\text{C}$ –precipitation correlations in June–August and negative $\delta^{13}\text{C}$ –humidity correlations in June–September. Shestakova et al. [80] found significant ($p < 0.05$) negative $\delta^{13}\text{C}$ –SPEI correlations in June and July, and positive correlation in the previous November. We also observed all the above-mentioned correlations (with precipitation, humidity, and SPEI); however, in the case of analyzed declining trees, we additionally observed significant correlations of $\delta^{13}\text{C}$ with these parameters in other seasons (spring, winter, and autumn). Stomatal conductance may be essential for ^{13}C discrimination in dry sites [82]. Low intercellular CO_2 concentrations have been demonstrated to diminish ^{13}C discrimination [83], raising $\delta^{13}\text{C}$ levels. The increased $\delta^{13}\text{C}$ values in the low total precipitation and humidity of summer months observed in our study can be the consequence of this decrease in discrimination. Negative correlations with SPEI indicate a high sensitivity of declining trees to drought conditions. Significant $\delta^{13}\text{C}$ –SPEI correlations in the summer months confirm the impact of summer droughts (often occurring in this region) on trees. It was particularly evident in the reduction in BAI and SPEI in August for declining trees (Figure 2b). The presence of only a single significant correlation between $\delta^{13}\text{C}$ and average and maximum temperature for both groups of trees, and many significant correlations between $\delta^{13}\text{C}$ and humidity (especially for trees in decline), support the hypothesis that moisture-related variables play a crucial role in ^{13}C discrimination [84].

The iWUE values we obtained are in the same range as those reported in the literature (e.g., [7,85,86]) for the same species in Europe. Further, the sharp increase in iWUE values that we observed for trees from both groups was also observed by other researchers (e.g., [87–89]). The largest increases in iWUE in Europe are recorded in temperate latitudes, which may be related to the drying trend, reflected in decreasing summer soil water content observed in this area [87]. Saurer M. et al. reported iWUE increases in several tree species in 35 locations in Europe between two periods: 1901–1910 and 1991–2000 [87]. The authors quantified a 39.8% increase in iWUE for *Pinus sylvestris* L. in Poland between the two periods specified [87]. The increase in iWUE found by us is higher (63% for healthy trees, 104% for declining trees) than the value found by Saurer M. et al. However, we underline that our analyses include data from the last 20 years, when the frequency of droughts was higher and the atmospheric CO_2 was at record levels. Therefore, an accelerated increase in iWUE in this area could be explained as a cumulative effect of water scarcity and increasing CO_2 . Sangüesa-Barreda et al. [90] compared BAI, $\delta^{13}\text{C}$, and iWUE characteristics of trees infested and noninfested by mistletoe and contemporarily affected by drought. The authors found enhanced defoliation and a significant reduction in BAI of infested trees for more than 10 years prior to sampling. The changes in iWUE between the infested and noninfested groups were noticed only for the last 5 years [90]. We found a similar relationship: the differences in BAI between healthy and declining trees occurred approximately 15 years before changes were visible in iWUE. In a study realized by Linares and Camarero [91], drought-sensitive tree species were analyzed, some of which began to decline as a result of the drought, while some remained in good health condition. Both groups of trees showed an increasing trend in iWUE; however, in the case of healthy trees, the growth was much higher at the end of the analyzed time range than for declining trees [91]. In the case of nondeclining trees, the authors also observed a significant link between iWUE and growth, which did not occur in the case of declining trees [91]. Our findings are coherent with

those. The lack of correlation between growth and iWUE in declining trees suggests a greater water loss compared with photosynthetic rates. Therefore, declining trees were less able to increase their water use efficiency compared with healthy trees. These trees may have reached a physiological threshold in their capacity to enhance iWUE when CO₂ rises [9,92]. Differences in the results for healthy trees suggest that they chose a different adaptive strategy under drought stress (the increased photosynthetic rate or alternatively the reduced stomatal conductance likely served to minimize water loss during periods of drought) [93]. The significant positive correlation found in the healthy trees between BAI and iWUE (Figure 5b), as well as the increasing trend in BAI chronology (Figure 2a), seems to confirm their adaptive strategy, which resulted in faster growth [94].

Of course, we should be aware of the possibility of the occurrence of genetic differences and other factors operating at the microlocal or local scale between trees from both groups. However, in the case of our research, the small, coherent study site and the proximity of trees make it unlikely that soil properties and microclimatic conditions caused the observed differences in drought sensitivity between healthy and declining trees, allowing these factors to be partially excluded.

5. Conclusions

The increased frequency of drought events occurring in recent years led to an increase in the mortality of weaker tree specimens. Our research has shown that changes in growth patterns can appear long before changes that can be observed by visual assessment of a tree's health (thinning tree crowns, presence of mistletoe, falling needles). Dendrochronological analyses might constitute a valuable tool enabling the early detection of poor forest conditions, thus allowing timely intervention aimed at preserving the ecosystem, its functions, and services. We also showed that trees growing in the same site condition may have different responses to the meteorological parameters and different resilience to drought. In particular, we demonstrated a much greater sensitivity of declining trees to changes in humidity, precipitation, and SPEI, as well as their lower resilience to drought episodes, which consequently led to their complete decline. The reduction in the iWUE value of declining trees compared with healthy trees, observed in the last 5 years of the analysis period, allow us to hypothesize that these trees were able to adopt different strategies to cope with drought stress. In particular, healthy trees minimized water loss during periods of drought, either through increased rates of photosynthesis or reduced stomatal conductance, which resulted in better condition of these trees.

Our study showed that dendrochronology enables early detection of poor forest health conditions and represents important knowledge for forest management strategies at local and regional scales.

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