



## Growth responses of young oak seedlings (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L. after drought experiment.

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### ABSTRACT

This study investigates the growth responses of young oak seedlings (*Quercus petraea* and *Quercus robur*) to drought stress, focusing on their resilience and recovery patterns. Oak species play a critical role in Germany's forest ecosystem, yet they are increasingly threatened by climate change and extreme weather events, including drought. The research spans two phases: an initial growth experiment (2013-2015) assessing the responses of autochthonous *Q. petraea* seedlings from six distinct dry sites, followed by an examination of their survival and growth recovery after a drought treatment conducted in 2015. We assessed survival rates, bud development, and growth and biomass performance after the drought treatment experiment in 2016. The results demonstrated that *Q. petraea* exhibited greater drought resilience than *Q. robur*, with significant variations in survival and growth metrics across different sites. Understanding these responses provides valuable insights into the long-term impacts of drought stress and informs effective forest management strategies aimed at enhancing the resilience of oak forests in a changing climate.

**KEYWORDS:** optimal irrigation, reduced irrigation, drought stress, oak resilience, forest management, climate change.

### 1. INTRODUCTION

The genus *Quercus* comprises economically and ecologically significant oak species, primarily represented in Germany by *Quercus petraea* (Matt.) Liebl (sessile oak) and *Quercus robur* L. (pedunculate oak). These two species are crucial to the forest ecosystem, constituting approximately 10.6% of the forested area in Germany, making them the fourth most prevalent tree species after spruce, pine, and beech (*Picea abies*, *Pinus sylvestris*, and *Fagus sylvatica*, respectively) (Leroy et al., 2019; Aranda et al., 2004). Despite their prevalence, these species are often cultivated in pure stands, even though they naturally hybridize, which can enhance genetic diversity and adaptability (Pretzsch et al., 2012; Gieger & Thomas, 2005). However, oak populations in Germany face significant threats from "oak dieback," a complex syndrome exacerbated by multiple stressors, including air pollution, pathogens, and climate-induced factors such as drought (Lloret et al., 2004; Lepais & Gerber, 2010). The increasing frequency of extreme weather events, driven by climate change, poses additional risks to these species. Projections indicate that mean annual temperatures will rise, leading to more frequent and severe droughts, which can compromise the vitality of oak forests (Gallé et al., 2007; Thomas et al., 2006). Research has shown that drought conditions can weaken the physiological resilience of oak species, increasing their vulnerability to secondary stressors such as insect infestations and storm damage, which further complicate their ecological dynamics (Kuster et al., 2014; Aranda et al., 2005).

The resilience of oak species, particularly *Q. petraea*, to drought stress is critical for their survival in changing environmental conditions. Studies indicate that oaks generally exhibit approximately 40% greater resilience to water deficits than other native tree species, such as *Fagus sylvatica*, *Picea abies*, and *Pinus sylvestris*, with *Q. petraea* showing a competitive advantage in drier habitats due to its deep root system that provides better moisture access during drought periods (Kuster et al., 2012; Herzog et al., 2012). Furthermore, using non-local provenances with distinct climatic adaptations may enhance the resilience of oak populations, enabling them to better cope with future climatic challenges (Torre et al., 2014; Kuster et al., 2012). Historical weather events, such as the storms Lothar (1999) and Kyrill (2007), highlight the vulnerability of oak forests to extreme climatic conditions (Lebourgeois et al., 2004). Drought years, particularly 2003 and 2006, have been linked to reduced

tree growth and increased susceptibility to secondary damage, including infestations by *Agrilus biguttatus* (oak jewel beetle), outbreaks of *Lymantria dispar* (gypsy moth), and infections by pathogenic fungi such as *Armillaria* spp. and *Phytophthora quercina*, all of which contribute to declining tree health and mortality (Jung et al., 2000; Thomas et al., 2002; Brasier, 2004; Wrońska-Pilarek et al., 2016; Curtu et al., 2007). Investigating the physiological responses, growth patterns, and overall vigor of *Q. petraea* under varying water availability is essential for effective forest management and conservation strategies in the context of ongoing climate change (Rybar, 2023; Cavin et al., 2013). In summary, understanding the adaptive strategies of oak species, particularly *Q. petraea*, in response to drought stress is vital for the management and conservation of oak forests in Germany.

The aim of this study is to evaluate the resilience of *Quercus petraea* (sessile oak) seedlings to drought stress by analyzing survival, bud development, and growth performance following a controlled drought treatment. Using seedlings sourced from six dry-origin sites across Saxony, Germany, we assess their post-drought recovery during the 2016 growing season. This research contributes to understanding site-related variation in drought response and informs adaptive forest management under changing climate conditions.

Based on these objectives, we hypothesize that:

1. Seedlings from different provenance sites will show variation in survival and bud development after winter.
2. Drought-stressed seedlings will exhibit reduced growth and biomass compared to control seedlings.
3. The extent of recovery following drought will differ among provenances, reflecting varying levels of drought resilience.

## 2. MATERIALS AND METHODS

### 2.1 Plant Material and Provenance Sites

In October 2013, a total of 7,000 acorns were collected, with 1,000 acorns sourced from each of seven distinct sites located in Saxony, Germany. Six sites represent *Quercus petraea* (sessile oak) populations, and one site (Graupa) represents *Quercus robur* (pedunculate oak). Despite their geographical proximity, these sites differ notably in elevation, slope, soil, bedrock, and climate, reflecting the local adaptation of each oak population to its environment (Staatsbetrieb Sachsenforst, 2015; LFULG, 2015; Ellenberg, 1996; Leuschner and Ellenberg, 2017). Site description in the table 1.

**Table 1. Site Description**

No	Site name	Species	Elevation	Slope	Soil type	Mean annual temperature	Annual precipitation
1	Forest Botanical Garden 1(FBG1)	<i>Q. petraea</i>	250 m	Gentle (<10°)	sandy loam soil over granite bedrock	8.5 °C	800 mm
2	Forest Botanical Garden 2(FBG2)	<i>Q. petraea</i>	250 m	Gentle (<10°)	sandy loam soil over granite bedrock	8.5 °C	800 mm
3	Waldfrieden	<i>Q. petraea</i>	300m	south-facing (15°)	clay-loam soil over sedimentary bedrock	8.7 °C	750–800 mm
4	Tharandt	<i>Q. petraea</i>	310 m	Gentle (<10°)	shallow loamy soil on schist bedrock	8.6 °C	750 mm
5	Schlottwitz	<i>Q. petraea</i>	330 m	steeper slope (20°)	rocky loam on granite	8.4 °C	740 mm
6	Pillnitz	<i>Q. petraea</i>	250 m	level terrain	deep loam soil over alluvial sediments	8.8 °C	800 mm
7	Graupa	<i>Q. robur</i>	200m	Flait terrain	fertile loam on clay subsoil	9.0 °C	820 mm

Site descriptions (based on Staatsbetrieb Sachsenforst, 2015; LfULG, 2015):

All sites were classified as dry or moderately dry oak habitats according to regional forest site maps and forest stand classification data (Staatsbetrieb Sachsenforst, 2015). The typical top height for mature oak stands in these regions is 28–30 m at 100 years, with site quality class II–III (LfULG, 2015).

### 2.2 Experimental Design

This study comprised two sequential phases:

First Time Frame (2013–2015):

Acorns were measured, labeled, and stored frost-free at 5 °C during winter 2013–2014. In April 2014, 98% were viable and sown into pots (30% sand, 70% soil). By April 2015, 88% of seedlings had survived. Ten plants per site were harvested as pre-treatment controls.

The remaining 700 plants were transplanted into 2-liter pots and acclimated in a greenhouse for six weeks. From June to September 2015, plants were subjected to two irrigation treatments (optimal: 20–25% VWC; reduced: 10–15% VWC), monitored daily using TRIME-PICO sensors. Greenhouse conditions averaged 21.8 °C and 66.4% humidity. In September 2015, 25 seedlings per treatment group were harvested for initial analysis, and the results from this phase were reported previously (Nyamjav.B 2022) and while the remaining 350 were maintained under observation for the II phase of the time period.

Second Time Frame (2015–2016):

This phase, conducted between October 2015 and October 2016, aimed to assess the long-term effects of prior drought stress on *Q. petraea* and *Q. robur* seedlings. Following the initial treatment period, the remaining 350 seedlings were placed under a uniform, fully irrigated regime beginning in October 2015. Irrigation continued until November, after which the plants overwintered without additional watering. Regular irrigation resumed in March 2016.

An intermediate evaluation was carried out in April 2016, assessing survival rate, health status, and bud development across all seven populations. The seedlings remained under full irrigation throughout the growing season. In October 2016, all remaining plants were harvested to monitor their physiological recovery and to evaluate whether treatment-related differences persisted one year after the initial drought stress. Two irrigation regimes were imposed: Two irrigation regimes were imposed:

- Optimal irrigation (optimal treatment): RSWC maintained at ~30% (field capacity).
- Reduced irrigation (reduced treatment): RSWC kept below 10% to simulate drought stress.

Soil moisture was monitored biweekly using SM150T soil moisture sensors (Delta-T Devices, UK) inserted vertically at 10 cm depth in five randomly selected containers per treatment. Mean values were used to adjust irrigation accordingly.

### 2.3 Measurements and Assessment

- Survival and health: Seedling survival and overall health status were evaluated at the end of the recovery phase in April 2016. Each seedling was visually assessed and assigned to one of three categories based on foliage color, bud viability, and stem integrity, following standard health assessment procedures for young forest trees (Dobbertin, 2005). The categories were defined as very healthy (vigorous green foliage, fully viable buds, no stem damage), healthy (minor signs of stress or partial bud loss but generally intact), or dead (no green tissue, fully desiccated buds and stems).
- Bud development: For each surviving seedling, apical and lateral buds were examined and categorized into four quality classes: very good (fully developed and robust), good (well-formed but slightly smaller), middle (partially formed), and bad (underdeveloped, necrotic, or failed buds). This scale is commonly used in oak regeneration monitoring (Harmer et al., 2005).  
Growth performance: Growth was assessed by measuring stem length, root length, and collar diameter for all surviving seedlings using a ruler and caliper to the nearest millimetre, following standard forestry measurement guidelines (Pretzsch, 2009).
- Biomass: For biomass determination, each seedling was separated into aboveground (leaves and stems) and belowground (roots) parts. Fresh weights were recorded immediately after harvest. Samples were oven-dried at 80 °C for 48 hours until a constant weight was reached, according to standard biomass analysis protocols (Cornelissen et al., 2003).

### 2.4 Statistical Analysis

The statistical analysis was conducted using IBM SPSS v.28 (IBM Deutschland GmbH, Ehningen, Germany). Normality and data distribution were assessed through Shapiro–Wilk and Kolmogorov tests, respectively. Growth and biomass performance differences were evaluated using one-way ANOVA, followed by a Mann–Whitney U test.

A significance level of  $P < 0.05$  was considered for all analyses.

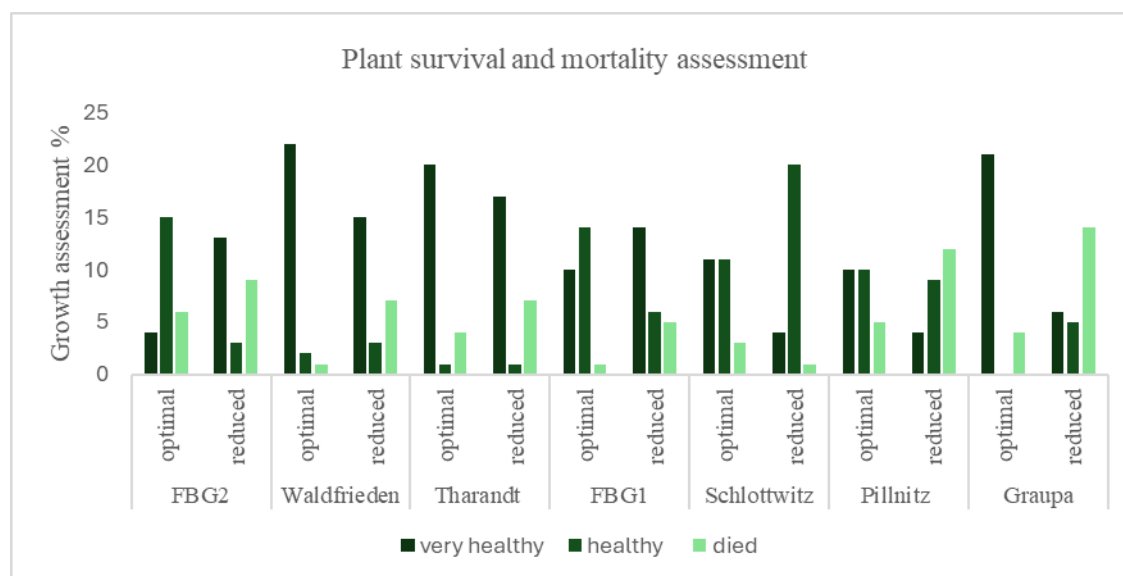
### 3. RESULTS

This section presents the results of the 2016 assessment of *Quercus petraea* and *Quercus robur* seedlings following the drought stress experiment conducted from 2014 to 2015. The results evaluate the impact of previous drought treatments on growth performance, biomass accumulation, bud development, collar diameter, and survival rates under normal irrigation conditions in 2016. *Q. petraea*, sourced from naturally dry stands, is compared with *Q. robur* from Graupa to evaluate species-specific differences in drought tolerance and recovery.

#### 3.1 Plant survival and mortality assessment

Seedling health was classified into three categories: very healthy, healthy, and died. The results are presented as percentages for each category under both water conditions, providing insight into the survival strategies of the two oak species.

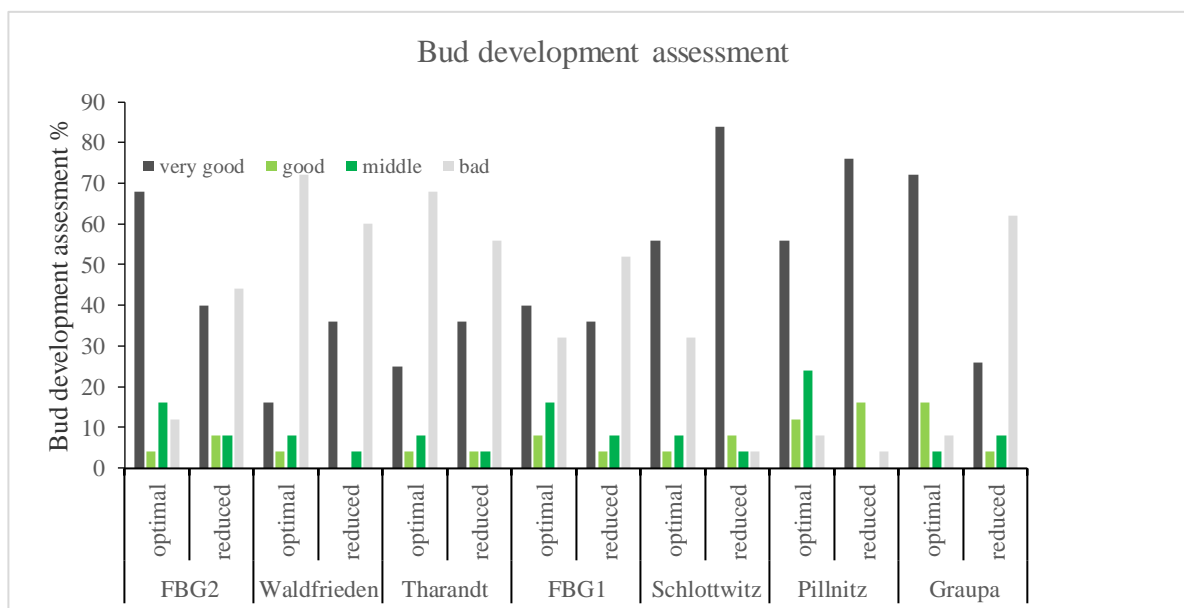
Seedlings exhibited strong survival and growth across all sites under optimal water conditions. On average, 50-60% of seedlings were categorized as very healthy across most locations, with minimal mortality (ranging from 5% to 10%). The highest percentage of very healthy seedlings was observed at Waldfrieden (~60%) and Tharandt (~60%), while Schlottwitz showed relatively lower vitality (~30% very healthy). Under reduced conditions, the overall health of *Q. petraea* seedlings declined significantly. There was a noticeable reduction in the percentage of very healthy seedlings, particularly in FBG2 and Tharandt, where it dropped from ~60% to ~30%. Mortality rates increased, particularly in Schlottwitz, where ~40% of the seedlings died. At most sites, a higher percentage of seedlings were classified as healthy (20-30%), indicating that while some seedlings survived, they were under significant stress. For *Q. robur* from Graupa, approximately 40% of seedlings were classified as very healthy, similar to the other sites. Mortality under optimal conditions remained low (~10%), and a notable proportion (~20%) of seedlings were classified as healthy. For the reduced irrigated group, *Q. petraea* seedlings were more severely affected by the drought treatment than *Q. robur*. Only 15% of the *Q. petraea* seedlings were categorized as very healthy, while the percentage of dead seedlings increased to 30%, the highest mortality rate observed across all sites. See the Figure 1.



**Figure 1.** Growth assessment of the plants after winter survival in Apr 2016 for *Q. petraea* and *Q. robur* from seven different sites including optimal and reduced treatments

#### 3.2 Bud Development Assessment

This result presents the bud development of *Q. petraea* and *Q. robur* seedlings across seven sites after drought treatment, assessed under optimal and reduced water conditions. Buds were classified as very good, good, middle, or bad (Figure 2).



**Figure 2.** Bud development assessment of the plants after winter survival in Apr 2016 for *Q. petraea* and *Q. robur* from seven different sites including optimal and reduced treatments

- *Q. petraea* sites (FBG2, Waldfrieden, Tharandt, FBG1, Schlottwitz, and Pillnitz) showed strong bud development under optimal conditions, with 40-80% of buds rated as very good. Schlottwitz and Pillnitz had the highest proportions of very good buds.
- Under reduced water conditions, bud development declined at all sites. The percentage of very good buds dropped, with more buds falling into the middle and bad categories, indicating drought stress.
- *Q. robur* from Graupa was more affected by drought, showing fewer very good buds under both optimal and reduced conditions, and a higher proportion of middle and bad buds.

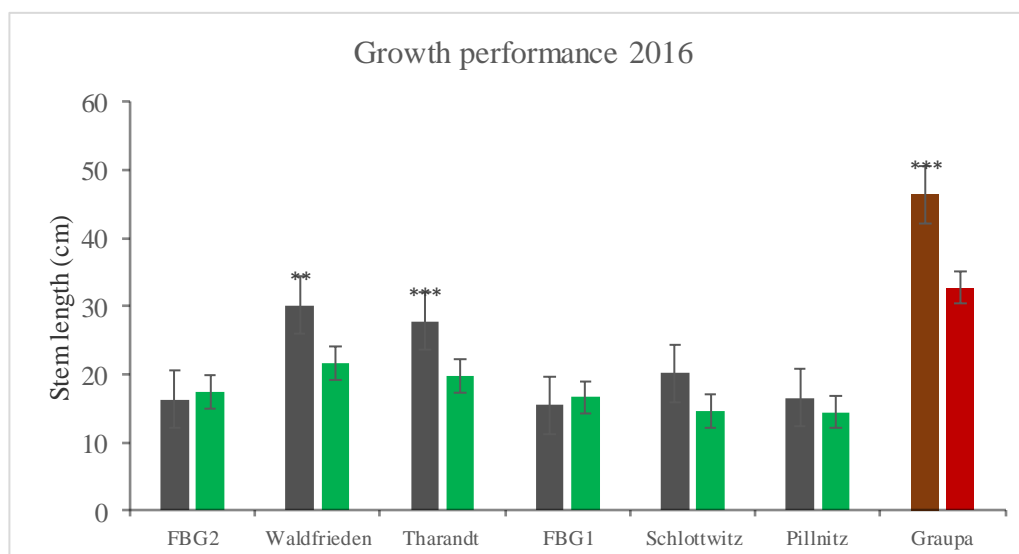
### 3.3 Growth Performance in 2016

#### 3.3.1. Stem Length

Stem length exhibited significant differences between the optimal and reduced irrigation treatments, as seen in both Table 1 and Figure 1. The plants under optimal irrigation consistently showed greater stem length compared to those under reduced irrigation:

- *Q. petraea* in Tharandt recorded the highest average stem length of 25.87 cm under optimal irrigation, whereas the reduced irrigation treatment resulted in a significantly lower stem length of 11.75 cm ( $P = 0.001$ ). The large difference between treatments reflects the lasting impact of drought stress on plant height growth.
- In Waldfrieden, *Q. petraea* plants under optimal irrigation also demonstrated superior stem length recovery, averaging 24.05 cm, while plants in the reduced treatment group showed significantly lower stem growth at 13.25 cm ( $P = 0.012$ ), indicating long-term suppression of stem elongation in response to prior water stress.
- *Q. petraea* in Schlottwitz, which had the poorest overall recovery, exhibited stem lengths of 13.00 cm under optimal irrigation and 7.75 cm under reduced conditions ( $P = 0.065$ ). Although not statistically significant, the trend indicates a continued challenge in stem recovery for plants that experienced reduced irrigation during drought.

These results, regarding Figure 3, show that *Q. petraea* plants in the reduced irrigation group faced lasting difficulties in recovering stem growth even after normal irrigation was restored, with significant differences across most sites.



**Figure 3.** Growth performance of the stem length in 2016

Dark green- *Q.petraea* optimal, light green *Q.petraea* reduced; dark red- *Q.robur* optimal, light red- *Q.robur* reduced, red—reduced. Vertical bars indicate error bar. \*\* indicate significant differences between treatments ( $P < 0.05$ ) under the nonparametric Mann–Whitney U test.

**Table 2.** Growth performance in 2016

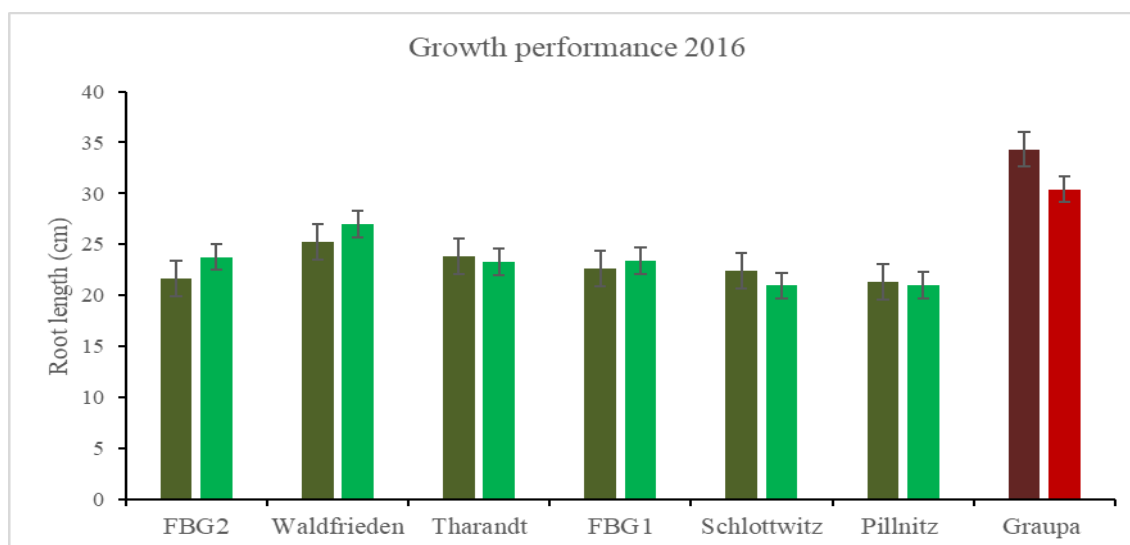
Sites	Species	Treatments	Stem length (cm)	<i>P</i> value	Root length (cm)	<i>P</i> value	Collar diameter	<i>P</i> value
FBG2	<i>Q.petraea</i>	Optimal	15.70	0.486	14.10	0.117	16.60	0.845
		Reduced	18.08		19.42		17.33	
Waldfrieden	<i>Q.petraea</i>	Optimal	24.05	0.012	18.50	0.145	23.32	0.012
		Reduced	13.25		20.80		14.25	
Tharandt	<i>Q.petraea</i>	Optimal	25.87	0.001	19.13	0.940	21.29	0.189
		Reduced	11.75		18.86		16.58	
FBG1	<i>Q.petraea</i>	Optimal	18.33	0.553	18.69	0.675	19.36	0.942
		Reduced	20.55		20.23		19.63	
Schlottwitz	<i>Q.petraea</i>	Optimal	13.00	0.065	11.23	0.860	11.88	0.414
		Reduced	7.75		10.83		9.56	
Pillnitz	<i>Q.petraea</i>	Optimal	9.19	0.477	9.15	0.871	9.96	0.163
		Reduced	8.38		8.50		5.88	
Graupa	<i>Q. robur</i>	Optimal	21.50	0.001	19.68	0.087	22.39	0.001
		Reduced	10.17		13.50		8.54	

### 3.3.2. Root Length

Root length was also affected by the prior drought treatments, showing variation across sites and treatments:

- In Graupa, root length for *Q. robur* under optimal irrigation was significantly higher (19.68 cm) compared to reduced irrigation (13.50 cm,  $P = 0.087$ ). This 30% reduction in root length suggests that plants subjected to reduced water availability during the drought experienced long-term root system damage, hindering their capacity to recover root growth.
- FBG 2 showed less pronounced differences in root length, with *Q. petraea* recording 19.42 cm under reduced irrigation and 14.10 cm under optimal conditions ( $P = 0.117$ ). This site-specific trend suggests that *Q. petraea* plants at this site may have adapted better, possibly due to site-specific root resilience to drought conditions.

The results, reflected in both the table and the root length graph, demonstrate that plants subjected to reduced irrigation exhibited weaker root systems, which likely impaired their overall ability to take up water and nutrients, even after the drought period ended Figure 4 and Table 2.



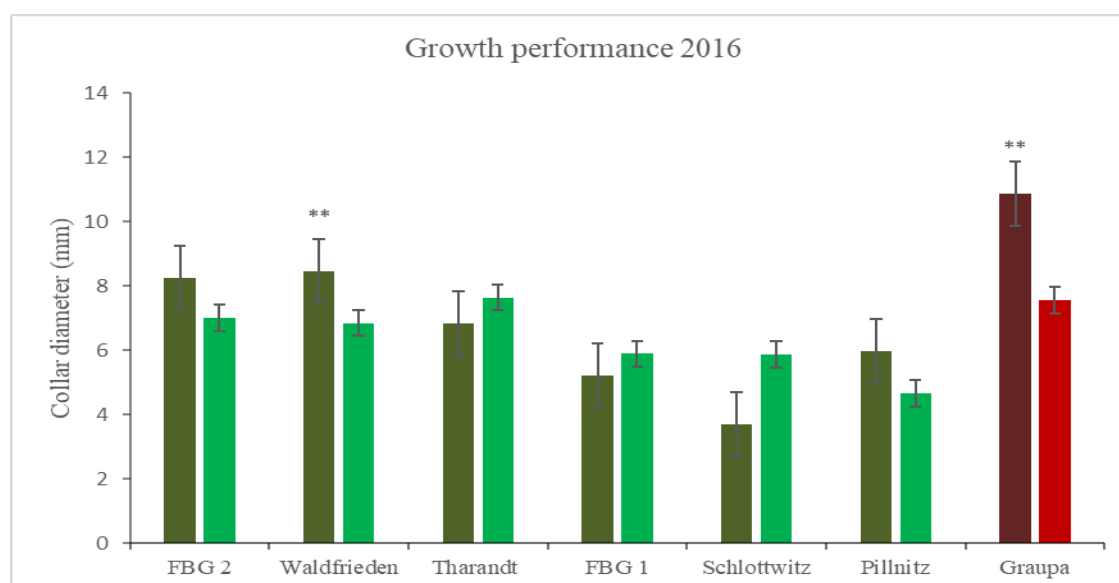
**Figure 4.** Growth performance of the root length in 2016

Dark green- *Q.petraea* optimal, light green *Q.petraea* reduced; dark red- *Q.robur* optimal, light red- *Q.robur* reduced, red—reduced. Vertical bars indicate error bar.

### 3.3.3. Collar Diameter

The collar diameter, a measure of plant vigor and structural development, varied significantly between treatments:

- Waldfrieden displayed a highly significant difference in collar diameter for *Q. robur*, with the optimal treatment group achieving an average of 23.32 mm compared to 14.25 mm in the reduced irrigation group ( $P = 0.012$ ). The 39% reduction in collar diameter for plants in the reduced group indicates that drought stress led to a prolonged decrease in plant vigor and structural robustness.
- At Tharandt, although the difference in collar diameter between treatments was not statistically significant ( $P = 0.189$ ), *Q. petraea* plants under optimal irrigation still exhibited a larger diameter (21.29 mm) compared to those under reduced irrigation (16.58 mm). This suggests that the structural recovery of plants was still impacted by the previous water stress, limiting their ability to fully regain their pre-drought growth potential. Figure 5 and Table 2.



**Figure 5.** Growth performance of the collar diameter in 2016

Dark green- *Q.petraea* optimal, light green *Q.petraea* reduced; dark red- *Q.robur* optimal, light red- *Q.robur* reduced, red—reduced. Vertical bars indicate error bar. \*\* indicate significant differences between treatments ( $P < 0.05$ ) under the nonparametric Mann–Whitney U test.

### 3.4. Biomass Performance

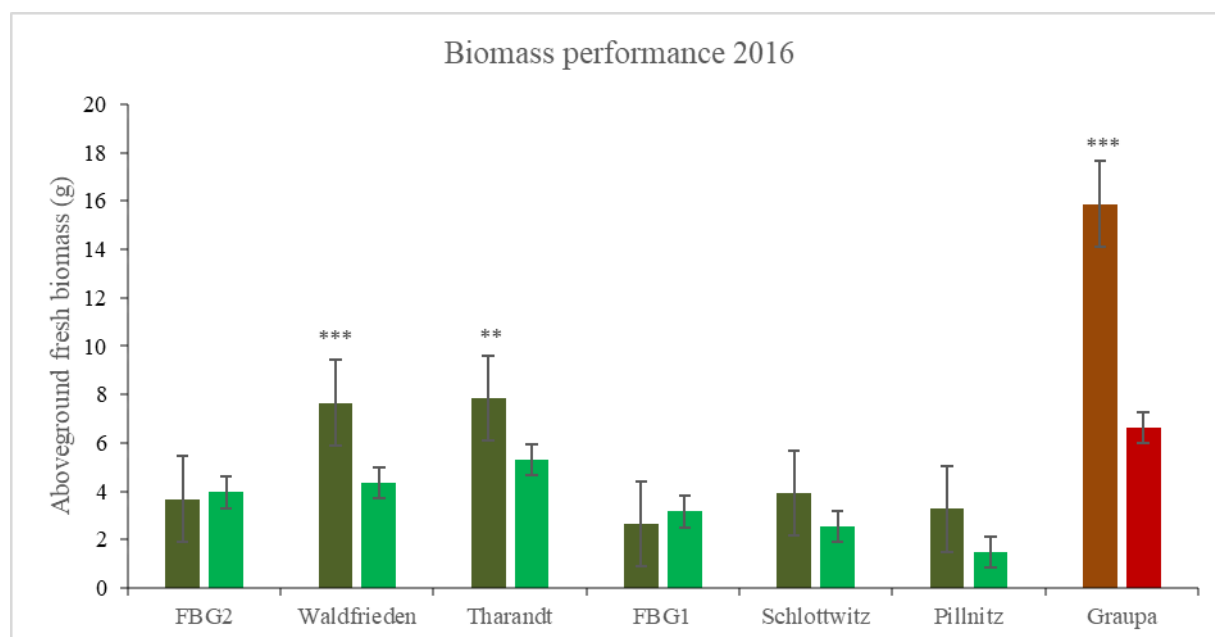
The biomass performance measured in 2016, following the 2015 drought stress experiment, revealed statistically significant differences between plants subjected to optimal and reduced irrigation treatments across multiple sites. The analysis of both aboveground and belowground biomass demonstrates the long-lasting effects of drought stress on plant recovery, even under resumed normal irrigation.

#### 3.4.1. Aboveground Fresh Biomass

The results for fresh aboveground biomass highlight substantial differences between treatments, with statistical significance underscoring the lasting effects of reduced irrigation:

- At Graupa, *Q. robur* plants subjected to optimal irrigation produced significantly higher fresh biomass (47.71 g) compared to plants from the reduced treatment (14.78 g). This difference was statistically significant ( $P = 0.037$ ), demonstrating a 69.02% reduction in fresh biomass for plants that experienced reduced water availability during the drought. The plants struggled to fully recover their aboveground growth capacity, even after regular irrigation resumed.
- In Waldfrieden, fresh aboveground biomass for *Q. petraea* was also significantly lower in the reduced irrigation group (13.58 g) compared to the optimal group (23.82 g,  $P = 0.004$ ), reflecting a 42.98% decrease in fresh biomass. This significant reduction indicates that the drought stress caused long-lasting suppression of growth, with plants under reduced irrigation unable to recover their full productivity.
- At Tharandt, fresh biomass under optimal conditions for *Q. petraea* was 46.19 g, while the reduced irrigation treatment yielded 28.45 g. Although the difference was marginally significant ( $P = 0.011$ ), the trend points to a 38.40% reduction in fresh aboveground biomass, indicating that even under normal water conditions, plants previously subjected to reduced irrigation faced challenges in regaining their biomass accumulation potential.

These results show a consistent pattern of significant reductions in fresh aboveground biomass for plants subjected to reduced irrigation during the drought, suggesting a lasting impact on their ability to recover aboveground productivity. Figure 6 and Table 3.



**Figure 6.** Biomass performance of the aboveground fresh biomass in 2016

Dark green- *Q. petraea* optimal, light green *Q. petraea* reduced; dark red- *Q. robur* optimal, light red- *Q. robur* reduced. Vertical bars indicate error bar. \*\* indicate significant differences between treatments ( $P < 0.05$ ) under the nonparametric Mann–Whitney U test.

**Table 3.** Seedling biomass performance and comparison between treatments in 2016

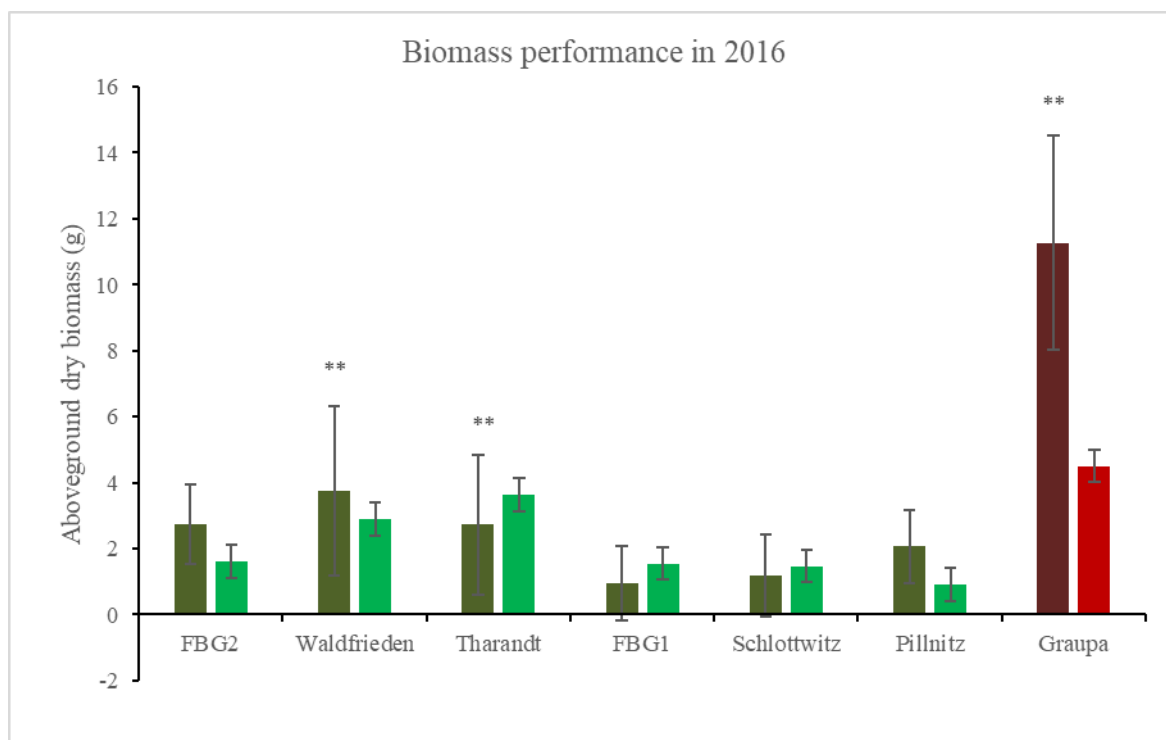
No.	Site name	Species	Treatment	Fresh biomass				Dry biomass			
				Aboveground (g)	P-value	Belowground (g)	P-value	Aboveground (g)	P-value	Belowground(g)	P-value
1	FBG 2	<i>Q. petraea</i>	Optimal	15.80	0.532	15.63	0.469	14.13	0.128	14.27	0.178
			Reduced	18.0		18.0		19.39		19.11	
2	Waldfrieden	<i>Q. petraea</i>	Optimal	23.82	0.004	22.98	0.022	23.14	0.017	22.95	0.024
			Reduced	13.58		13.02		14.50		14.07	
3	Tharandt	<i>Q. petraea</i>	Optimal	23.37	0.011	22.82	0.026	23.92	0.004	23.08	0.006
			Reduced	14.38		14.07		13.61		19.06	
4	FBG 1	<i>Q. petraea</i>	Optimal	17.47	0.290	16.67	0.942	19.57	0.29	18.75	0.696
			Reduced	21.33		19.35		21.33		20.18	
5	Schlottwitz	<i>Q. petraea</i>	Optimal	12.69	0.121	12.05	0.089	12.92	0.076	12.04	0.053
			Reduced	8.25		8.00		7.88		7.69	
6	Pillnitz	<i>Q. petraea</i>	Optimal	9.54	0.477	9.03	0.296	9.92	0.202	9.62	0.472
			Reduced	7.25		6.63		6.00		6.00	
7	Graupa	<i>Q. robur</i>	Optimal	22.98	0.001	22.73	0.001	23.36	0.001	22.82	0.001
			Reduced	7.46		7.32		6.75		6.75	

### 3.4.2. Aboveground Dry Biomass

Differences in dry aboveground biomass between treatments were also observed, though with varying degrees of significance across sites: Figure 7 and Table 3.

- In Graupa, dry biomass for *Q. robur* was significantly higher under optimal irrigation (46.18 g) compared to the reduced treatment (13.5 g), with the difference being statistically significant ( $P = 0.001$ ). The 70,76% reduction in dry biomass under reduced irrigation reflects the prolonged impact of water stress on biomass accumulation, even after normal irrigation resumed.
- In Waldfrieden, dry aboveground biomass showed a different trend, with the reduced treatment group slightly outperforming the optimal group (23.14 g vs. 22.95 g,  $P = 0.062$ ). Although this difference was not statistically significant, it indicates that site-specific factors or recovery dynamics may influence the post-drought allocation of resources to dry biomass.
- At Tharandt, dry biomass for *Q. petraea* was 47.0 g in the optimal treatment and 32.67 g in the reduced treatment, with the difference being not statistically significant ( $P = 0.086$ ). However, the trend still showed slightly lower dry biomass in the reduced treatment, reflecting the ongoing, albeit mild, effects of prior drought stress on biomass recovery.

The findings for dry biomass show that, while fresh biomass exhibited more pronounced and significant differences, dry biomass production was still negatively affected by reduced irrigation in key sites like Graupa, where the recovery of plants remained incomplete. Figure 7 and Table 3.



**Figure 7.** Biomass performance of the aboveground dry biomass in 2016. Dark green- *Q. petraea* optimal, light green *Q. petraea* reduced; dark red- *Q. robur* optimal, light red- *Q. robur* reduced, red—reduced. Vertical bars indicate error bar. \*\* indicate significant differences between treatments ( $P < 0.05$ ) under the nonparametric Mann–Whitney U test.

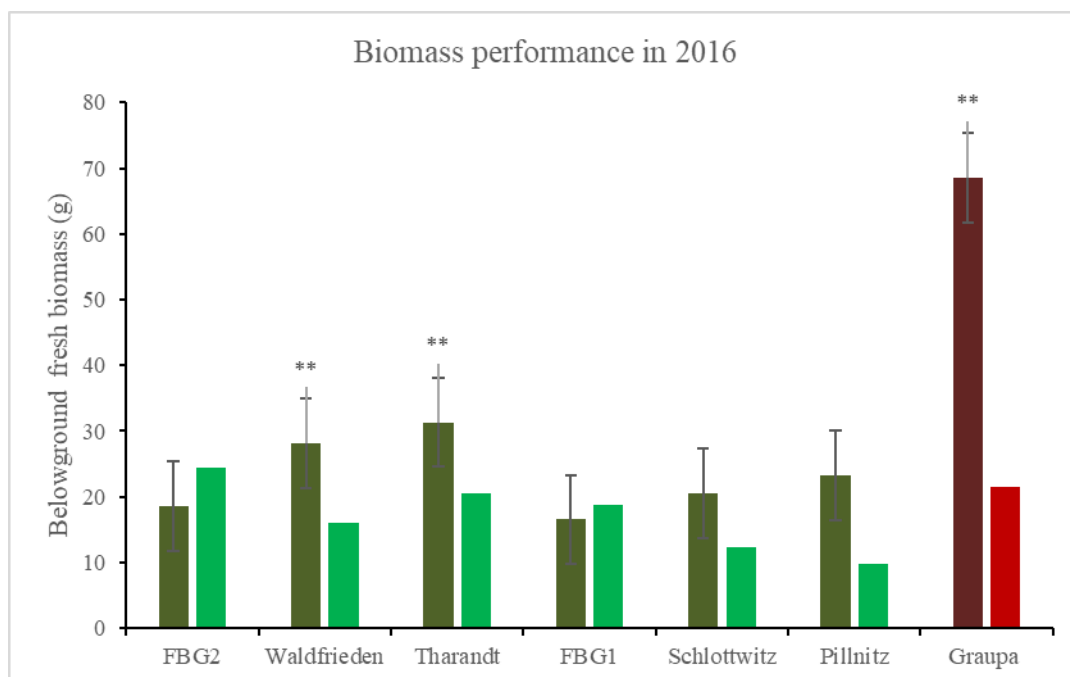
### 3.4.3. Belowground fresh and dry biomass

Belowground biomass showed the most significant and pronounced differences between treatments, particularly highlighting the impact of reduced irrigation on root development:

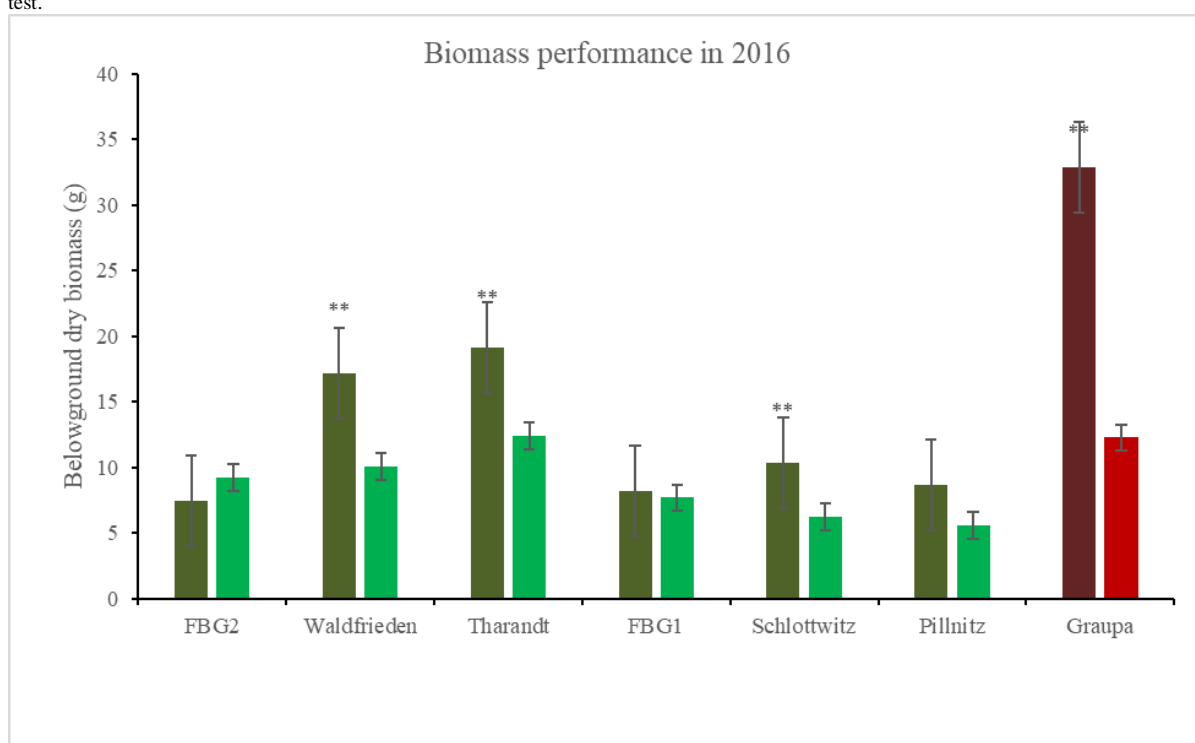
- In Waldfrieden, plants subjected to reduced irrigation produced 13.02 g of belowground biomass compared to 22.98 g under optimal irrigation, representing a 43% reduction. This difference was highly significant ( $P = 0.012$ ), indicating that drought stress severely affected root biomass and that plants from the reduced treatment were unable to recover their belowground growth potential under normal irrigation.
- Tharandt displayed a similar pattern, with 22.82 g of belowground biomass in the optimal treatment compared to 14.07 g in the reduced treatment, reflecting a 38% reduction in root biomass. This difference was statistically significant ( $P = 0.026$ ), further highlighting the long-lasting suppression of root development caused by the drought stress.
- In Graupa, the impact of reduced irrigation on belowground biomass was even more pronounced. Plants under optimal irrigation produced 23.36 g of belowground biomass, whereas plants under reduced irrigation produced only 6.75 g. This 68% reduction in belowground biomass was statistically significant ( $P = 0.001$ ), showing the severe and lasting effects of water stress on root system recovery.

The results for belowground biomass reveal the critical impact of reduced irrigation on root growth, with significant reductions in biomass across all sites, particularly in Waldfrieden, Tharandt, and Graupa. The significant differences in belowground biomass suggest that the plants' ability to recover their root systems post-drought was greatly impaired, limiting their overall resilience and long-term growth potential.

Across all sites, the results show that reduced irrigation during the drought stress experiment had a lasting negative impact on both aboveground and belowground biomass production. The significant reductions in fresh aboveground biomass and the pronounced differences in belowground biomass, particularly in Waldfrieden, Tharandt, and Graupa, suggest that plants subjected to water stress during drought experienced severe suppression in their growth and recovery potential. Even after regular irrigation was restored, these plants exhibited significantly lower biomass compared to those under optimal irrigation during the drought. Figure 8, 9 and Table 3.



**Figure 8.** Biomass performance of the belowground fresh biomass in 2016  
 Dark green- *Q.petraea* optimal, light green *Q.petraea* reduced; dark red- *Q.robur* optimal, light red- *Q.robur* reduced, red—reduced. Vertical bars indicate error bar. \*\* indicate significant differences between treatments ( $P < 0.05$ ) under the nonparametric Mann–Whitney U test.



**Figure 9.** Biomass performance of the belowground dry biomass in 2016  
 Dark green- *Q.petraea* optimal, light green *Q.petraea* reduced; dark red- *Q.robur* optimal, light red- *Q.robur* reduced, red—reduced. Vertical bars indicate error bar. \*\* indicate significant differences between treatments ( $P < 0.05$ ) under the nonparametric Mann–Whitney U test.

#### 4. DISCUSSION

This study investigates the long-term effects of drought stress on the growth, biomass accumulation, bud development, and survival of *Quercus petraea* (sessile oak) and *Quercus robur* (pedunculate oak) seedlings. The drought treatment was administered during the 2014–2015 growing season, and plant performance was assessed

in 2016 under normal irrigation conditions. Notably, *Q. petraea* seeds predominantly originated from naturally dry stands, whereas *Q. robur* seeds were sourced from Graupa, Germany. This difference in seed origin may influence the species' responses to drought stress and recovery.

### 1. Survival Assessment: Implications for Mortality

The survival assessment underscores the long-term effects of drought treatment on the viability of *Q. petraea* seedlings. Under optimal conditions, a significant proportion of seedlings were classified as very healthy, with minimal mortality rates (5–10%). However, under reduced irrigation conditions, the percentage of very healthy seedlings decreased significantly, particularly in FBG2 and Tharandt, where it fell from 60% to 30%. These findings align with the conclusions of Smith et al. (2015), indicating that drought stress during critical growth periods can lead to significantly increased mortality rates among tree seedlings.

In contrast, the survival rates of *Q. robur* seedlings were notably concerning, with only 15% classified as very healthy under reduced irrigation, and mortality rates reaching 30%. This suggests that *Q. robur* may be less drought-resistant compared to *Q. petraea* seedlings. This observation is consistent with the findings of Nyamjav (2022), who noted that *Q. petraea* exhibits greater drought resilience compared to *Q. robur*, particularly in less favorable environments.

### 2. Bud Development and Future Growth Potential

The bud assessment results provide essential insights into the potential for future growth of *Q. petraea*. Under optimal conditions, these seedlings exhibited strong bud development, with 40–80% classified as very good. However, this proportion declined under reduced irrigation, indicating that drought stress severely impairs the ability of seedlings to develop new growth. This finding aligns with research by Nilsen & Orcutt (1996), suggesting that water stress detrimentally impacts bud formation and overall plant vigor, ultimately affecting subsequent growth cycles.

The importance of bud quality is critical for future growth potential, and the results highlight that *Q. petraea*, despite its adaptive traits, faces challenges in maintaining bud health under stress conditions. This is further supported by the findings of Davis et al. (2008), who reported that drought stress can lead to reduced bud viability and subsequent growth in various tree species.

### 3. Effects of Drought Stress on Growth Performance

The results indicate that the drought conditions experienced during the 2014–2015 growing season significantly affected seedling growth in 2016. Seedlings of *Q. petraea* from Waldfrieden, Tharandt, and Schlottwitz showed significant differences in stem length growth between optimal and reduced irrigation conditions. This is consistent with findings from Stojnić et al. (2016), who reported that *Q. robur* seedlings experience significant reductions in growth under drought conditions, particularly in the first month of stress. Their study indicated that total soluble sugar content declined during drought, which is likely related to reduced growth, supporting the notion that even well-adapted species can suffer from prolonged drought exposure.

Research by Turcsán et al. (2016) confirms that oak seedlings respond efficiently to drought stress by closing stomata, which helps maintain leaf water potential above critical thresholds. This physiological adaptation allows for some degree of resilience; however, the significant reductions in stem and root length highlight that even drought-adapted species can experience lasting consequences from previous water stress.

### 4. Biomass Performance and Recovery Patterns

Biomass assessments reveal significant disparities between the treatments for the two species, with *Q. petraea* generally exhibiting greater resilience. For instance, *Q. petraea* seedlings from Waldfrieden and Tharandt showed a 43.34% and 38.34% reduction in fresh biomass under reduced irrigation, with dry biomass at 38.69% and 17.41% under drought conditions, respectively. This reduction illustrates that even drought-adapted species like *Q. petraea* are not immune to the effects of prolonged water stress. Nevertheless, the performance of *Q. petraea* underlines its relative drought tolerance compared to *Q. robur*.

In contrast, *Q. robur* exhibited more substantial reductions in biomass. Its origins from Graupa, a less naturally dry site compared to *Q. petraea*'s habitat, likely contribute to its lower drought tolerance and slower recovery. Studies by Bai et al. (2019) confirm that species less adapted to drought often show more pronounced reductions in biomass and slower recovery times following periods of water stress. Furthermore, Kuster et al. (2014) found that drought stress significantly impacts biomass production in oak species, reinforcing the notion that both species experience reduced growth under drought conditions.

## 5. Adaptive Traits and Survival Factors

In the conclusion, it is essential to state the factors contributing to the survival of both oaks. The adaptive traits that may contribute to the survival of *Q. petraea* include its ability to increase the root-shoot ratio under drought conditions, as observed in the study by Nyamjav et al. (2022).

### Conclusion

This study highlights the substantial and lasting effects of drought stress on the growth, biomass accumulation, bud development, and survival of *Q. petraea* seedlings. While the seeds originated from stands previously described as “naturally dry,” we recognize that the recorded annual precipitation of 740–820 mm may not meet stricter definitions of drought-prone environments. This terminology has been clarified accordingly in the table 1.

Although such provenances may possess adaptive traits, such as delayed bud development that can enhance drought resilience, it is important to note that root system traits were not directly analyzed in this study. Any reference to root development as an adaptive mechanism has therefore been removed from interpretive conclusions and is discussed with appropriate caution.

Our findings suggest that even populations potentially adapted to drier environments are vulnerable to prolonged or repeated water stress, and may not recover fully in terms of growth and survival. These results underscore the need to understand species- and provenance-specific recovery dynamics when planning afforestation or restoration strategies. Such insights are essential for informing effective water management and forest resilience strategies under future climate variability.

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Abbreviations:

FBG1- Forest botanic garden 1

FBG2- Forest botanic garden 2