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Original article

Crown structure, growth, and drought tolerance of true service tree (*Sorbus domestica* L.) in forests and urban environments

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ABSTRACTS

True service tree (*Sorbus domestica* L.) is a rare native species of Central Europe. It grows well in dry and warm environments and may consequently be well adapted to the expected future climate further north. It is considered a potentially suitable species for climate change adaptation in forests and urban environments. In this study, we used total tree height, stem diameter, and crown dimensions of true service trees in Germany, southern Scandinavia, northern Italy, and Slovakia to determine the species' allometric relationships and space requirements. Additionally, we used tree cores from Germany and Slovakia and stem discs of a true service tree in Copenhagen to study growth patterns and drought stress response. Throughout, we compared to oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.), as common and well-studied species. Our results indicated that true service tree and the two oak species have similar growth patterns and space requirements. True service tree and oak both had a fast growth in their youth, followed by a gradual reduction at later stages. The crown projection area of true service tree was similarly influenced by competitors as that of oak, indicating a similar sensitivity towards competition. Likewise, we identified similarities in growth response to drought and, hence, drought tolerance. Due to their comparable growth pattern and drought tolerance, we hypothesise that oak, in many regards, can be used as a model species for the management of true service tree.

1. Introduction

As a xerophilic species with a core distribution in the south and south-east of Europe, the true service tree *(Sorbus domestica* L.) is considered a potentially suitable species for climate change adaptation in forests and urban environments. Even if there is still a debate to which extent the species is native to Central Europe (Rueda Salgueiro et al., 2006; George et al., 2016; Špíšek et al., 2018; Špíšek et al., 2022), it fits in very well in native forest ecosystems in this region. In contrast to many other forest tree species, true service tree is pollinated by insects and its fruits are considered of high ecological value. Furthermore, its conspicuous flowers add to the aesthetics of urban environments and forest settings (Kausch-Blecken von Schmeling, 2000) and, depending of management practice, true service tree may contribute to the production of highly valuable timber (Coello et al., 2013; Piagnani et al., 2018).

The true service tree is rarely used in cities and forests as managers generally prioritise tree species that are easier to manage due to their higher competitive strength, yield, and shade tolerance. Moreover, planted individuals of true service tree are very susceptible to *Neonectria ditissima,* a fungus that causes an uncurable canker and may lead to complete dieback (Keil, 1996). Naturally regenerated individuals of true service tree are scarce, and natural regeneration is generally absent (BLE, 2013). As a reflection of this rareness, the literature on true service tree (Supplementary Tables S1–S3) includes little quantitative information on ecological and silvicultural characteristics. Concerning the crown allometry, so far, only Paganová et al. (2015) described different types of crown shapes for true service tree in urban environments in Slovakia. Studies on general allometric relationships, also in forests, are scarce. Kausch-Blecken von Schmeling (2000) and Skovsgaard and Graversgaard (2013) published some basic height-diameter and age-height relationships. Cisneros et al. (2006) and Coello et al. (2013) published recommendations for stand density and potential target diameters, however, without presenting their underlying methodology.

Most studies on tree growth focus on young trees, typically seedlings or saplings and generally cover only the first few years of growth (Paganová et al., 2014; Kunz et al., 2016). Other than that, there are only

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a few experimental plots including true service tree. In Germany, a provenance trial across several states, is no longer active (Tabel et al., 2001). In Denmark and Sweden, experiments have been planted to observe the survival, growth and health of different provenances (Skovsgaard and Graversgaard, 2013; Jansson, 2017; Skovsgaard et al., 2017); likewise in Slovakia (Bakay and Rovná, 2021) and Italy (Piagnani et al., 2018).

Descriptions of the drought tolerance and heat sensitivity of true service tree are often based on observations and considerations of the current range of distribution (e.g., Cisneros et al., 2006; Rueda Salgueiro et al., 2006; Coello et al., 2013; Gonin et al., 2013) rather than on experimental evidence or other quantitative indicators. However, due to the use of true service tree for fruit production, its range of distribution is highly influenced by human activity (Drapier, 1993; Kausch-Blecken von Schmeling, 2000; Skovsgaard and Graversgaard, 2013), resulting in potentially biased interpretations and conclusions. So far, only two dendroecological studies of adult trees have been carried out and with contrasting results: Kunz et al. (2018) found the drought tolerance of true service tree to be marginally lower than that of oak, while Camarero et al. (2023) found it to be marginally higher.

In summary, the site-specific growth characteristics, drought tolerance and allometric relationships of true service tree are essentially unknown or, at least, unquantified. Such information is needed to derive relevant management prescriptions, spacing requirements throughout the lifetime of individual trees and the selection of tree species for specific locations. Especially in cities, where space is often limited and claimed by many stakeholders, accurate information about the crown allometry and growth patterns may be crucial. Also, the shading and cooling potential of a species can be assessed based on crown allometry, as the crown size is highly related to a tree's photosynthetic active radiation (APAR) and leaf area (Binkley et al., 2013; Forrester et al., 2017b). In this context, addressing the crown dimensions of solitary or so-called open-grown trees is essential as trees in cities generally grow with no or only a few competitors. In forests, the knowledge of allometric relationships enables the manager to assess the space requirements of a species throughout the rotation and, in turn, the need for release from competitors and to plan the weight and frequency of thinning operations. Knowledge of the height development pattern aids the selection of suitable species mixtures and their suitable management. The assessment of the drought response aids in the assessment of need for maintenance by, for example, watering during drought periods in urban environments and of the overall suitability of true service tree for cities and forests under climate change conditions. The objective of the study presented here was to quantify the crown size and the growth of true service tree subjected to different degrees of inter-tree competition. Data was collected along a north-south gradient in Italy, Slovakia, Germany, Denmark, Sweden and Norway. The response to drought was analysed based on stem cores from true service trees in Germany and Slovakia and stem discs from a city tree in Copenhagen, Denmark. Throughout, the measurements and growing patterns of true service tree were compared to sessile oak (*Quercus petraea* (Matt.) Liebl) and pedunculate oak (*Quercus robur* L.), from hereon referred to as 'oak', growing nearby under similar conditions. The two oak species are well-known across most of Europe (Mölder et al., 2019), both in forests and cities and their growth and response to drought have been quantified and modelled in great detail (Mette et al., 2013; Pretzsch, 2019; Meyer et al., 2020; Stimm et al., 2022). This makes it easy for landscape, forest, park and city tree managers to compare and assess our results and to put them in the context of their local circumstances.

Our study addressed and quantified the following topics:

1. The allometric relationships of the crown and stem of true service tree.
2. The site-specific growth pattern of true service and its response to drought.
3. A comparison of these characteristics to those of oak.
4. The suitability of true service tree for urban environments and forests under climate change, interpreted based on these quantitative indicators.

2. Materials and Methods

2.1. Sites

We measured true service trees in four regions in Central Europe: southern Scandinavia, northern Franconia in Germany, western Slovakia and the province of Bolzano in South Tyrol, Italy (Fig. 1). The occurrences in Germany and Slovakia are within the core distribution range of true service tree (Caudullo et al., 2017). The Scandinavian trees were growing outside the core range but in regions where the climate is expected to shift towards warmer temperatures and more drought, similar to the species' current distribution (Skovsgaard and Graversgaard, 2013). Climatic conditions in South Tyrol are similar to those of the core distribution range. By covering both core populations and marginal individuals, we could give a broad overview of the growth of true service tree growing under different climatic conditions. In Scandinavia and South Tyrol, we measured a large proportion of the trees known to occur in these regions. In Germany and Slovakia, local forest authorities provided maps with the locations of individual trees. Based on those, we selected stands with a relatively high proportion of true service tree and measured trees across the range of size classes. The measurements in Germany and Scandinavia took place during spring 2022. Trees in South Tyrol were measured during winter 2022, and trees in Slovakia during spring 2023.

On each site, we additionally measured some oak trees. Selection criteria were a similar dbh (dbh and d are used interchangeably for the stem diameter at 1.30 m above ground level) as the true service tree and a position in close vicinity to the true service tree, but without crown contact. The oaks were chosen to grow within a similar species composition, stand density, site conditions and of similar age. We measured trees growing in forest stands, urban environments, and parks. In contrast to forest stands, we defined urban environments and parks as locations within cities and locations where trees were standing in a continuous grass cover without a closed canopy. This included city parks, arboreta, and "Castelfeder"-nature reserve in South Tyrol, where trees stood in extensively managed meadows or between vineyards. The type of locations, the annual mean temperature, the precipitation sum, and the number of trees measured per site are described in greater detail in the Supplementary tables.

2.2. Field measurements

All trees were measured for total height (h), dbh, crown length (cl = total tree height minus height above ground level of the lowest living branch (excluding epicormic branches)) and crown radius (cr = distance from the centre of the stem to the point of projection of the crown periphery, as measured at ground level) in eight cardinal directions. For single trees in South Tyrol, however, we only measured the crown projection in four directions (due to inaccessibility of some trees standing on steep slopes). Crown projection area (cpa) was derived based on mean cr as $cpa = (cr_{mean})^2 \cdot \pi$.

Trees taller than approximately 8–9 m were measured for height by using a Haglöf Vertex 4 and trees of lower height by using a telescopic height pole (1 cm - scale), cr was measured using a tape (10 cm reading accuracy) or a Haglöf Vertex 4, and dbh was measured using a tape (1 mm scale). Furthermore, we measured the distance and the diameter of surrounding trees with a dbh larger than 5 cm within a radius corresponding to one third of the height of the true service tree. The competition status of each tree was assessed based on the Hegyi competition index (CI) (Hegyi, 1974). CI was calculated using the following equation:

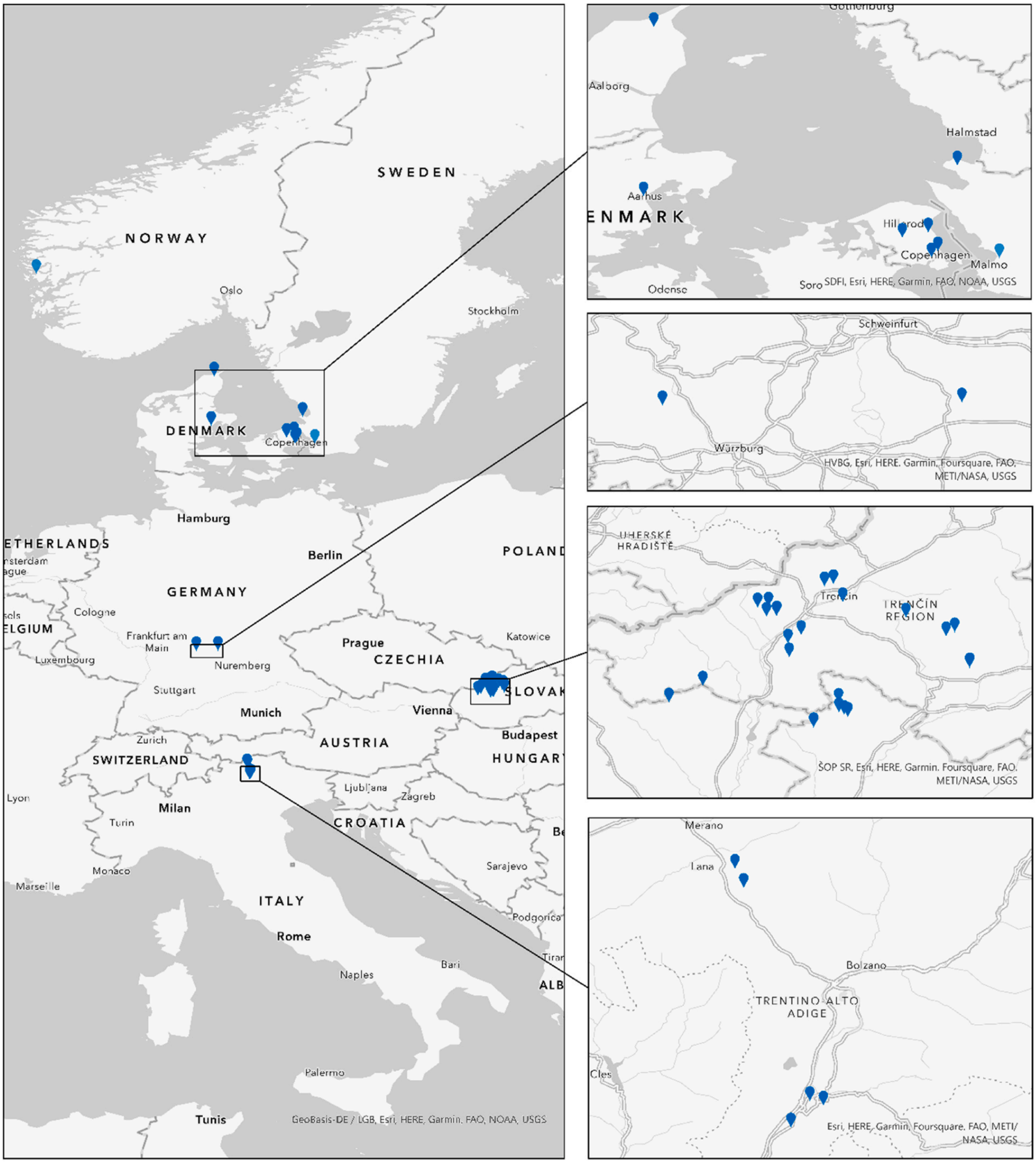

Fig. 1. Locations of trees and stands measured for this investigation.

$$CI_i = \sum_{j=1}^{n} \frac{d_j}{d_i \cdot dist_{ij}} \tag{1}$$

where d_i is the diameter of the central tree, d_j is the diameter of the competitor, and $dist_{ij}$ is the distance between the central tree and the competitor, and subscripts i and j identify the individual trees. The measurements are summarized in Table 1.

In the stands in Germany and at two locations in Slovakia, we also collected increment cores. The cores were taken at 1.30 m above ground level in Gerolzhofen and at 0.3 m in Zellingen and Slovakia, in both cases using a Haglöf increment corer. The oaks at each site were also cored. We took two cores per tree, one from the north and one from the east.

In April 2022, we felled a true service tree in Copenhagen. The tree was located next to a bitumen road near the strait of Øresund and was open-grown (hence, without competition from other trees). After cutting the tree, we collected five cross-sectional stem discs at 0.3 m, 2.0 m, 4.0 m, 6.0 m and 8.0 m above ground level, respectively. As the main stem was branching out at a height of 1.4 m, we selected the largest of the multiple stems above this point for disc extraction. In October 2013, we measured the stem of a true service tree located in the park in Alnarp, Sweden. The upper part of the stem had broken off during a recent windstorm. The entire stem was measured at intervals of 25–50 cm up to 10 m above ground level. Stem volumes were derived based on these measurements, and stem profiles were sketched based on measurements at 1–2 m intervals (to 'smoothen out' irregularities in the stem profile).

Table 1
Mean values of measured variables by country.

Country	Species	dbh [cm] ± sd	h [m] ± sd	cpa [m2] ± sd	n_{comp}	CI	n_{cores}
D	oak	34.08 ± 12.28	22.68 ± 4.35	36.98 ± 30.41	12.05	1.98	26
	true service tree	33.09 ± 15.23	21.08 ± 4.68	38.42 ± 30.81	11.74	2.09	19
DK	oak	37.97 ± 31.33	15.18 ± 6.61	89.27 ± 73.37	0.00	0.00	0
	true service tree	20.93 ± 28.72	8.25 ± 4.94	40.61 ± 25.55	3.75	0.46	1
IT	oak	23.89 ±9.18	11.79 ± 2.95	29.27 ± 25.55	5.00	1.05	0
	true service tree	23.65 ± 11.29	12.69 ± 4.64	26.5 ± 25.46	4.75	1.24	0
SK	oak	35.46 ± 6.68	23.34 ± 4.62	21.47 ± 17.87	11.21	1.77	0
	true service tree	34.53 ± 11.34	21.96 ± 4.28	30.47 ± 50.29	9.10	1.49	0
N	true service tree	23.5 ± 2.12	8 ± 1.41	50.2 ± 9.74		0.00	0
S	true service tree	9.5 ± 4.95	6	19.03		0.00	0

2.3. Meteorological data

For the locations in Slovakia and Scandinavia, we extracted monthly precipitation sums and temperature data (mean, maximum and minimum) from extrapolated grids of the Climate Research Unit (CRU) for the years from 1901 to 2021 (Harris et al., 2020). For the two locations in Germany, we used the grid data of the German Weather Service (DWD) (DWD Climate Data Center, 2022). For locations in Italy, we used data from the climate station in Auer for Neumarkt, Castelfeder and Montan and data from the station Meran Gratsch for Gargazon and Burgstall. The data is accessible through the open data portal for climate data of South Tyrol (https://data.civis.bz.it/). The de Martonne aridity index (DMI) (Martonne, 1926) was calculated for each site using the formula $\mathrm{DMI} = \mathrm{P}/(\mathrm{T}+10)$, where P is the sum of annual precipitation and T the annual mean temperature. For a general characterisation of local aridity, we averaged the DMI from 1992 to 2021.

For the assessment of drought years, we used the standardised precipitation evaporation index (SPEI) (Vicente-Serrano et al., 2010). This multiscalar index includes both precipitation and temperature and is, therefore, suitable for assessing drought. The SPEI includes the potential evapotranspiration, which we calculated using the Hargreaves equation (Hargreaves, 1994; Droogers and Allen, 2002). To compare the fit of different time spans, we calculated the SPEI for 3, 6, and 12 months and calculated seasonal averages for spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February).

2.4. Tree-ring measurements

Each increment core was dried, glued onto a wooden board and sanded with increasingly finer abrasive paper from 800 to 4000 grits, thereby improving the visibility of tree-ring borders. Likewise, each stem disc was grinded and measured from north and east directions from bark to pith. We measured tree-rings to the nearest 0.001 mm using a digital positioning table (Kutschenreiter and Johann Digital-positiometer, Biritz and Hatzl GmbH, Austria). The resulting curves underwent a visual crossdating where years of common growth over all curves were used as reference (Speer, 2010). The cross-dating was then statistically verified using the dplR package in R (Bunn, 2008, 2010; Bunn et al., 2022).

2.5. Allometry

The relationships between h and dbh and between cpa and dbh of a tree were described based on the classical model for allometric relationships: $y = a * x^{\alpha}$ (Huxley, 1932; Teissier, 1934), where x and y are measurements of tree organs and a and α are allometric constants. We used the log-transformed version $\ln y = \ln a + \alpha \ln x$. The exponent α describes the allocation of resources between x and y. Theoretic approaches assume that there are fixed, generalised allometric exponents describing the allometric relationships between tree variables under ideal growing conditions (e.g., 2/3 for the h-d-relationship and 4/3 for the cpa-d-relationship) (West et al., 1997; Enquist et al., 1998). In reality, allometric exponents often deviate from these ideal values and depend on site and growing conditions (Poorter et al., 2012; Forrester et al., 2017; Del Río et al., 2019; Fortin et al., 2019). The resulting species-specific variation of the allometric exponent can be interpreted based on the relationship between two variables in an allometric corridor (Pretzsch, 2010). The width, course, and upper and lower limits of this corridor reflect the ecological characteristics of a given species.

We displayed the allometric corridor by fitting a quantile regression (Koenker, 2005) to different conditional quantiles of the log-transformed h-d and cpa-d relationships. We chose the 0.05 and 0.95 quantiles to represent the lower and upper border of the corridor and the 0.5 quantiles to represent the typical median relationship. Each quantile represents different growing situations and the respective shift in resource allocation. The 0.05 quantile describes the situation in which a tree allocates its resources in favour of diameter growth vs. h or cpa growth (e.g., with low lateral competition or under a canopy of taller trees). The 0.95 quantile describes the opposite, i.e., a decreased diameter growth compared to h or cpa growth, as is the case for crowns of open-grown trees with few or no competitors as we often find them in urban environments. We assume that these two quantiles represent the extreme growth forms of a tree species. Below or above them, we can expect a dieback of the tree, e.g., due to light deficiency.

We calculated the confidence intervals for each regression model by rank inversion (Koenker, 2005).

To consider the influence of climate and competition on crown size and to test species-specific differences between oak and true service tree, we extended the allometric formula to a linear mixed model based on the following equation:

$$\ln(cpa) = a_0 + a_1 \cdot \ln(dbh_{ij}) + a_2 \cdot CI_{ij} + a_3 \cdot DMI_{ij} + a_4 \cdot species_{ij} + a_5 \cdot type_i + a_6 \cdot CI_{ij} \cdot species_{ij} + plot_i + \varepsilon_{ij} \quad (2)$$

where a_0, … a_6 are parameters to be estimated, species refers to tree species (true service tree or oak), type refers to the tree's location in a park or a forest setting, plot is the random intercept on plot as defined in Table 1, $\varepsilon \sim N(0, \sigma_\varepsilon^2)$ is the residual error, subscript i refers to tree no. i, subscript j refers to tree no. j, and all other symbols are as previously explained in the text.

The variables used in the model were scaled to the standard deviation and centred around the mean to enhance comparability and comprehensibility (Schielzeth, 2010). The variable type reflects whether a tree is growing in an urban or forest environment and thus accounts for the related variability in management and growth conditions (Supplementary Table S4).

The model assumptions of homoscedasticity and normality of residuals were checked visually based on qq-plots and by plotting standardized residuals vs. fitted values. The plots indicated no violation of model assumptions.

The stem volume of the main axis of each tree was calculated based on the length and mid-diameter of each stem section, assuming a cylindric form of each section. The volume of all sections was added up to the total stem volume.

2.6. Growth and drought stress response

2.6.1. Tree ring analysis

We detrended the tree-ring data to remove age- and management-related trends from the curves. Detrending was carried out based on a 30-year spline with a 50% frequency cut-off (Cook, 1990; Cook and Peters, 1997; Klesse, 2021). This smoothens the age-trend-related low-frequency variation in the series while retaining the high-frequency and inter-annual variation. The results of the detrending were dimensionless ring-width indices (RWI).

Next, we averaged the two measurements for each tree, using Tukey's bi-weight robust mean and built average RWI chronologies for each site (Cook, 1990). The chronologies were truncated for years with measurements of less than 5 trees. To assess the quality of the tree-ring series, we calculated common dendroecological statistics (interseries correlation, signal-to-noise ratio, mean gleichläufigkeit and subsample signal strength; see supplementary table S1).

The tree-ring data from the stem discs of the tree in Copenhagen were used to reconstruct the three-dimensional stem development. The height development was reconstructed using a standard interpolation method from the data obtained from different stem heights (Carmean, 1972; Newberry, 1991). Diameters between the stem discs were estimated by linear interpolation between tree-rings. Here, all values refer to under-bark diameters.

2.6.2. Selection of drought years

We evaluated climate-growth relationships of the tree-ring chronologies of oak and true service tree to determine which climatic variables were most influential on growth. As climate variables, we used the monthly precipitation and temperature, the monthly SPEI3, SPEI6, and SPEI12, and the seasonal means of all variables. Subsequently, we calculated bootstrapped Pearson's correlation coefficients between the variables and the species-specific site chronologies, using a stationary bootstrap (Politis and Romano, 1994) with 1000 samples. We also calculated mean correlation coefficients over all sites for each species by transforming each correlation coefficient using Fisher's z scores (Silver and Dunlap, 1987), averaging them and finally back-transforming them (see Table S2).

We selected drought years by using the SPEI12 for July. This index had a high correlation with annual growth for both species over all stands. It also reflects the previous year's weather conditions and the two peaks of diameter growth of true service tree within the vegetation period (Camarero et al., 2023). For each location we selected drought years from 1965 onwards (see Table S3). Following the classifications of Slette et al. (2019), we selected all years with a SPEI12 in July of less than -1.5 (categories severely dry and extremely dry).

2.6.3. Quantifying the drought stress response

Drought stress tolerance was assessed through Lloret indices of resistance (Rt), recovery (Rc) and resilience (Rs) (Lloret et al., 2011), calculated as follows:

$$Rt = Dr / PreDr$$

$$Rc = PostDr / Dr$$

$$Rs = PostDr / PreDr$$

where Dr is the growth in the drought year, PreDr is the growth in a period before the drought, and PostDr is the growth in a period after the drought year.

The hypothesis of different mean values of Rt, Rc and Rs between oak and true service tree was tested based on bootstrapping (n = 1000) the differences in mean and calculating 95 % confidence intervals based on the bootstrapped values.

Following the recommendations of Schwarz et al. (2020), we compared different periods before and after drought (2, 3 and 5 years) to choose the most reliable one. As we found no evident differences between periods, we selected a pre- and post-drought period of two years, thereby limiting the influence of other events affecting the growth of trees.

In addition to the original Lloret indices, we calculated the so-called line of full resilience (Schwarz et al., 2020). This line indicates the level of recovery a tree would have to reach to obtain its pre-drought growth level. The line is derived by putting Rc, Rs and Rt in relation to each other and setting Rs to 1:

$$Rc = Rs / Rt$$

$$Rc = 1 / Rt$$

The species-specific relationship follows a power function with the following formula:

$$Rc = a \cdot Rt^b$$

2.7. Statistical software

All statistical analyses were carried out using R (R Core Team, 2022)

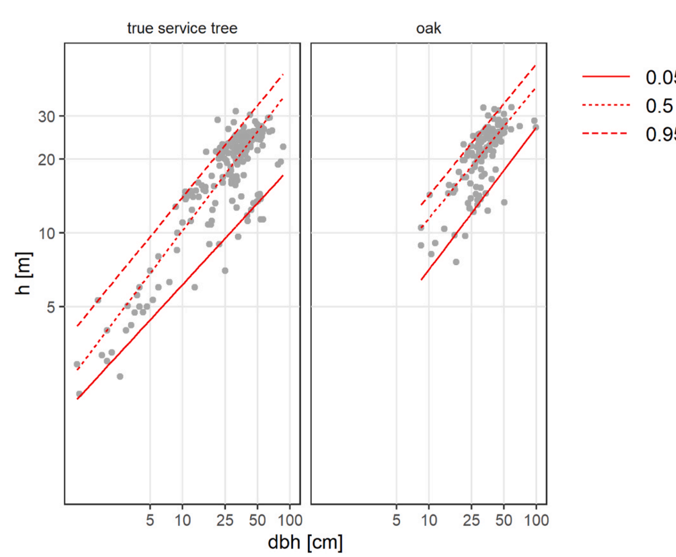

Fig. 2. Allometric relationships between dbh [cm] and h [m] for true service tree and oak. The upper line represents the 0.95 quantile, the middle line the 0.5 quantile-regression and the lowest line the 0.05 quantile (parameter estimates in Table 2).

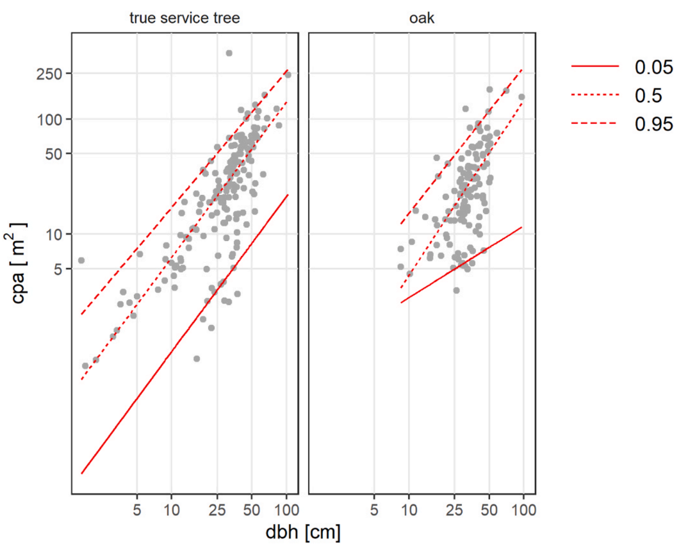

Fig. 3. Allometric relationships between dbh [cm] and cpa [m^2] for true service tree and oak. The upper line represents the 0.95 quantile, the middle line the 0.5 quantile regression and the lowest line the 0.05 quantile (parameter estimates in Table 2).

and R Studio (Posit team, 2022) using the packages of the tidyverse (Wickham et al., 2019). Quantile regressions were calibrated in the package quantreg (Koenker, 2022) and mixed-effect models in the packages lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017).

3. Results

3.1. Allometry of crown and stem

The fitting of quantile regressions resulted in the curves displayed in Fig. 2 and Fig. 3. We observed similar values for true service tree and oak for both the height-diameter (h-d) and the cpa-diameter relationships (Table 2). The h-d relationship values of the allometric exponent for true service tree ranged between 0.48 and 0.58. Especially for the 0.95 quantile, both species' intercept and allometric exponent values were similar or identical. For the 0.5 quantiles, only the intercepts differed, but marginally. For the 0.05 quantile, the values for oak were larger than for true service tree.

For the cpa-d relationship, the intercepts of the 0.95 and the 0.5 quantiles were smaller for oak than for true service tree. The values for the allometric exponent were, however, larger. In the 0.05 quantile the intercept was smaller for true service tree and the allometric exponent was larger.

The trees in Copenhagen and Alnarp, clearly had a somewhat pyramidical stem profile. Stem increment mainly occurred on the lower parts of the stem, up to a height of 2 m. The annual radial increment in the upper parts of the stem was much lower, resulting in a highly tapered stem (Fig. 4). The total volume of the stem in Copenhagen was 0.77 m^3 and of the stem in Alnarp 2.38 m^3.

The linear mixed model (Eq. 2) detected a significant effect of dbh, competition and location type on cpa (Table 3) for the overall data set. There were no significant differences of crown size or sensitivity towards competition between species.

3.2. Growth and drought stress response

3.2.1. Growth

True service tree and oak in Germany and Slovakia showed similar growth patterns over the period of measurements (Fig. 5) with mostly lower increments for higher dbh.

The height-age curve derived from stem analysis of a tree in Copenhagen (Fig. 6a) indicated fast growth until around 20–22 years of age. Subsequently, growth slowed down and the curve flattened. The transition from fast to slow height growth was rather abrupt and the growth rate was essentially constant in each of these two phases. In contrast, the growth on dbh was almost linear until around 50 years and only slowed down considerably at around 70 years (Fig. 6b).

3.2.2. Drought stress response

Considering the species-specific indices of resistance, recovery, and resilience (Fig. 7), we could not reject the hypothesis of equal means. Comparing the line of full resilience (Fig. 8), we found a similar drought response in both species. For lower resistance values, both species were lying under the line of full resilience but intersecting it already at a resistance value below 1. After that, the curves for both species were proceeding above the line of full resilience.

3.3. Comparison to oak

Combining our results and observations from the literature, we summarise the differences between oak and true service tree in

Table 2
Parameter estimates for the quantile regression models describing the relationship between h and dbh and between cpa and dbh.

Model	Quantile		True service tree		Oak	
			a	α	a	α
ln(cpa) = a + α × ln(d)	0.05	estimate	-3.15	1.35	-0.41	0.63
		conf. low	-9.97	0.57	-9.16	0.05
		conf. high	-0.69	3.00	1.20	3.05
	0.5	estimate	-1.28	1.35	-2.04	1.52
		conf. low	-1.78	1.28	-3.22	1.19
		conf. high	-1.07	1.47	-0.91	1.85
	0.95	estimate	0.11	1.18	-0.22	1.27
		conf. low	-0.51	0.84	-0.78	0.81
		conf. high	1.32	1.36	1.44	1.55
ln(h) = a + α × ln(d)	0.05	estimate	0.72	0.48	0.62	0.58
		conf. low	0.31	0.47	-0.01	0.45
		conf. high	0.76	0.56	0.91	0.68
	0.5	estimate	0.99	0.58	1.20	0.54
		conf. low	0.81	0.55	0.88	0.43
		conf. high	1.09	0.63	1.66	0.63
	0.95	estimate	1.40	0.54	1.42	0.54
		conf. low	1.37	0.04	0.89	0.19
		conf. high	3.57	0.55	3.30	0.70

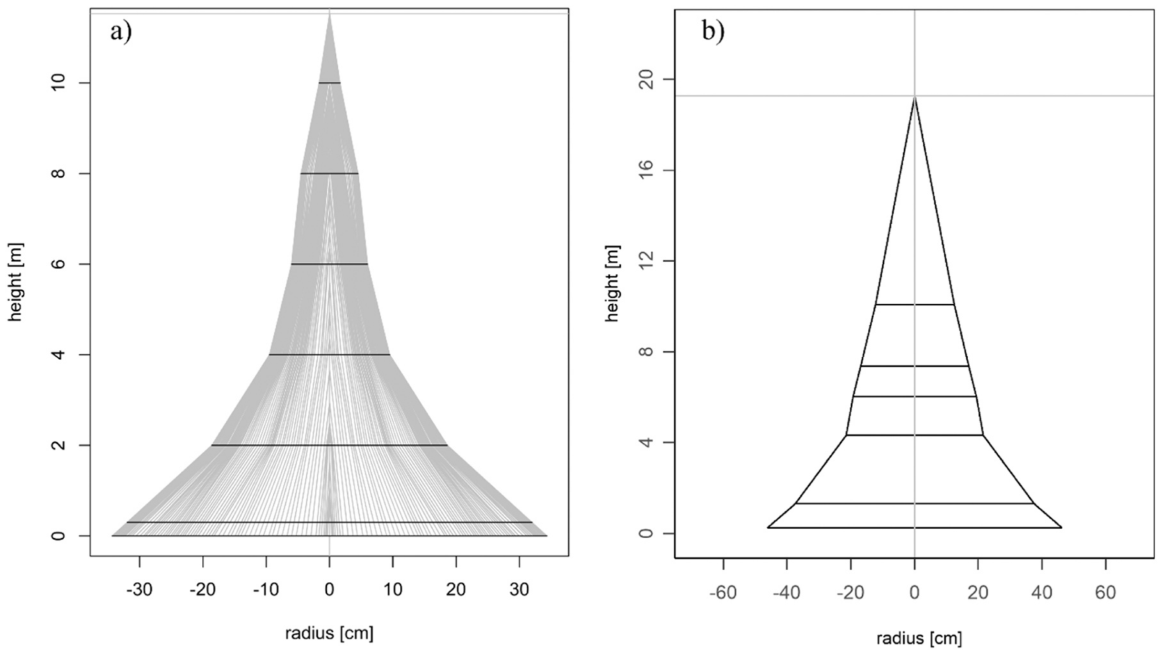

Fig. 4. Stem diagram based on the stem analysis of a true service tree in Copenhagen (a) and section diameter measurements of a tree in Alnarp (b). Black lines refer to the height of stem discs; grey lines indicates the annual increment.

Table 3
Parameter estimates for Eq. 2. df = degrees of freedom, CI = competition index, DMI = de Martonne Index, sd = standard deviation.

	Parameter	Estimate	Standard error	df	statistic	p-value
	Fixed Effects					
	Intercept	2.41	0.15	29.92	15.71	0.00
	ln dbh	1.12	0.07	329.83	16.19	0.00
	CI	-0.18	0.06	332.52	-3.22	0.00
	Species: true service tree	0.08	0.06	319.57	1.34	0.18
	Type: park	1.09	0.32	32.89	3.35	0.00
	DMI	0.01	0.06	34.67	0.23	0.82
	CI: true service tree	0.02	0.06	323.91	0.33	0.74
	Random effects					
Plot	sd_Intercept	0.66				
Residual	sd_Observation	0.53				

allometry, growth and drought response in the following overview:

	True service tree	Oak
h-d allometry	Similar for both species, but a steeper increase for oak at the 0.05 quantile. Essentially identical height growth for both species.	
cpa-d allometry	Similar for both species, but a steeper increase for true service tree at the 0.05 quantile. Larger crown size for smaller trees of true service tree; otherwise, similar space requirements.	
Sensitivity to competition	Our analysis: no significant difference between species. Literature: higher sensitivity of true service tree	
Growth	Both species: fast height growth in youth, which later decreases, in line with Skovsgaard and Graversgaard (2013).	
Drought tolerance	Our analysis: similar drought tolerance. Literature: oak less drought tolerant (Camarero et al., 2023) or more (Kunz et al., 2016; Kunz et al., 2018)	
Aboveground CO_2 storage	Age 50: 1.51 tons (Orlandi et al., 2022)	Age > 46 : 1.18 tons of carbon (Weissert et al., 2017), equals 4.33 tons of CO_2
PM10 uptake	1.16 g/m^2 (Orlandi et al., 2022) - 1.01 g/m^2 (Fares et al., 2020)	0.7 g/m^2 (Fares et al., 2020)

4. Discussion

4.1. Allometry of crown and stem

4.1.1. Quantile regression

The exponents of the h-d relationship for both oak and true service tree were lower than the expected general exponent of 2/3, while the exponents of the cpa-d relationships were not significantly different from the assumed 4/3 (West et al., 1999). We therefore recommend using the species-specific exponents from our study for the h-d relationship to avoid an overestimation of height. For assessing crown sizes the 4/3 exponent can be applied.

The parameters of the h-d relationship for oak and true service tree had similar values for the 0.95 and 0.5 quantiles. So, planners and managers can rely on their experience with oak to assess the potential height of true service tree. Concerning the crown development, the crown projection area of true service tree in the 0.95 quantile was slightly higher than for oak. The quantile is associated with city trees as these trees are often growing as essentially solitary trees and represent an exceptional case along the competition gradient. The higher space requirements should be considered in urban planning. For the 0.05 quantile, true service tree had smaller crown sizes for small dbh values than oak. However, this reversed with increasing dbh. Following the classification of Pretzsch et al. (2015), true service tree has the same

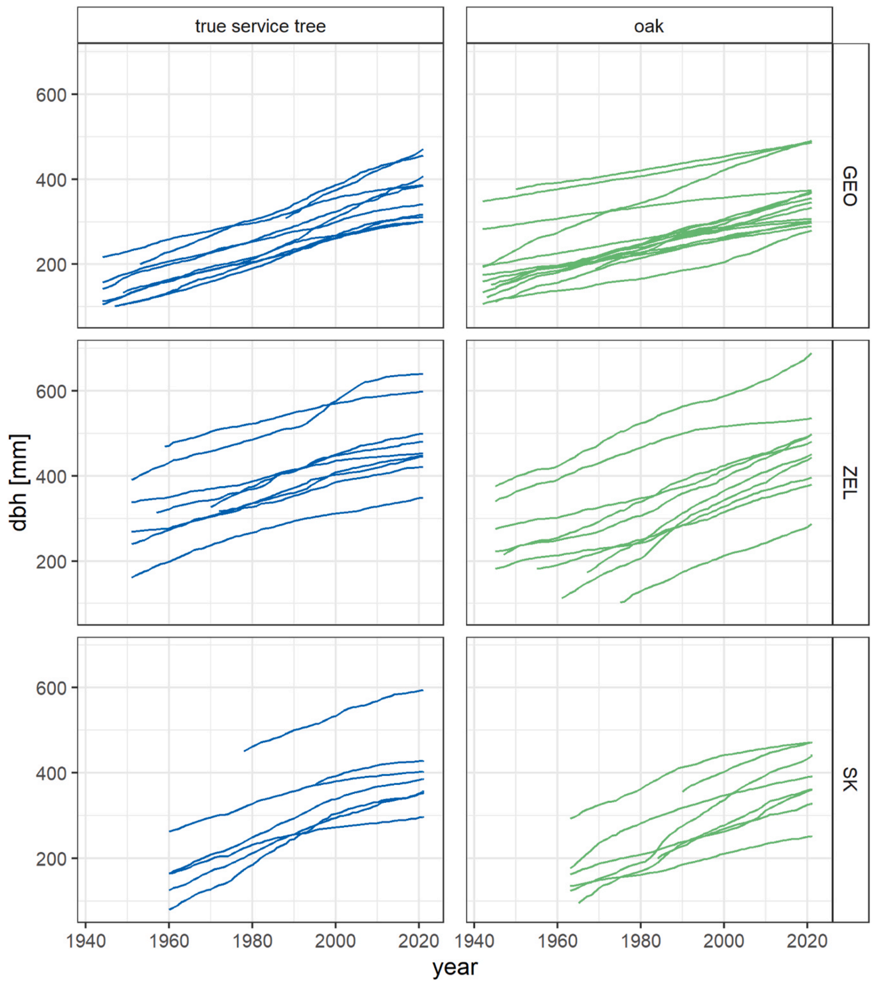

Fig. 5. Species-specific diameter growth of trees over age for true service tree and oak. Legend: GEO = Gerolzhofen, ZEL = Zellingen, SK = Slovakia.

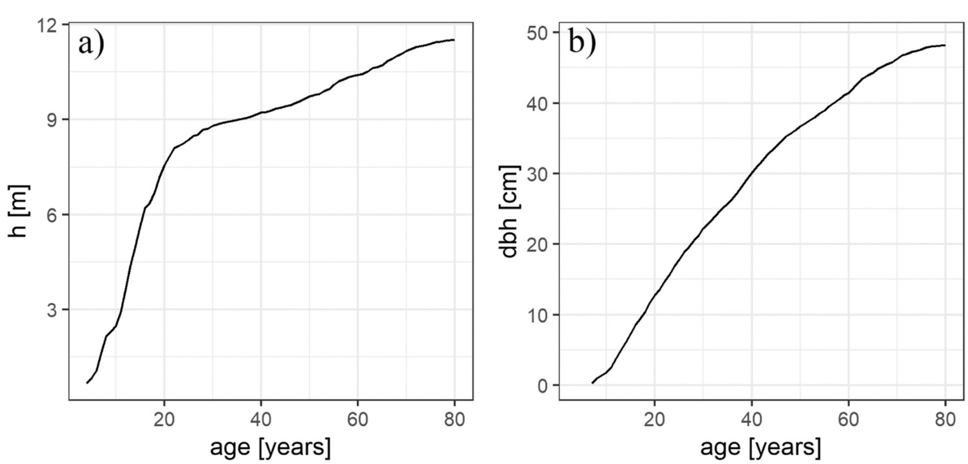

Fig. 6. Height-age curve (a) and diameter-age curve (b) derived from a stem-analysis of a true service tree in Copenhagen.

crown type as black locust (*Robinia pseudoacacia* L.) and European hornbeam (*Carpinus betulus* L.). These species more rapidly expand their crown when free from competition, as compared to tree species with other crown types. In contrast, *Sorbus arnoldiana* (the hybrid of *Sorbus aucuparia* and *Sorbus discolor*) which has a leaf shape similar to that of true service tree, was found to have a rather low shade intensity (Rahman et al., 2015).

Overall, our results for the crown and stem allometry of true service tree were similar to those of other scientists, even when comparing across different regions in Europe. Kausch-Blecken von Schmeling (2000) published h-d values for true service tree in south German forests that are very similar to our results. He also described maximum heights of up to 34 m for true service tree. The tallest tree in our dataset is a Slovakian tree with a height of 31.4 m. In German forest stands, we found several trees with a height of around 29 m. We could also confirm the existence of crown diameters of more than 20 m (Skovsgaard and

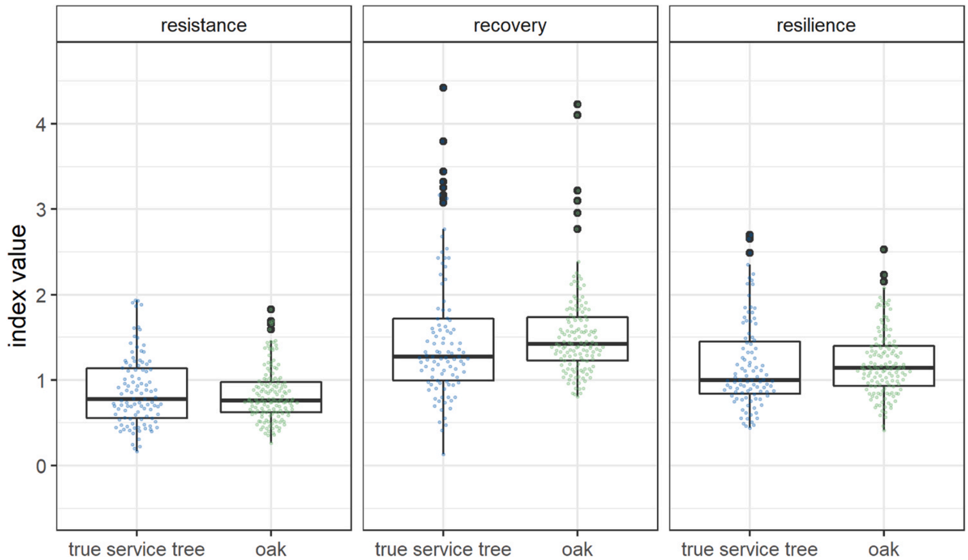

Fig. 7. Boxplots showing the values of the Lloret indices of recovery, resilience and resistance for true service tree and oak. The lower and upper hinges represent the 25th and 75th percentiles, respectivelz, and the horizontal line represents the location of the median. The upper and lower whiskers extend from the hinges to the values closest to a multiple of 1.5 of the interquantile range. All data beyond the whiskers are displayed as outlier points.

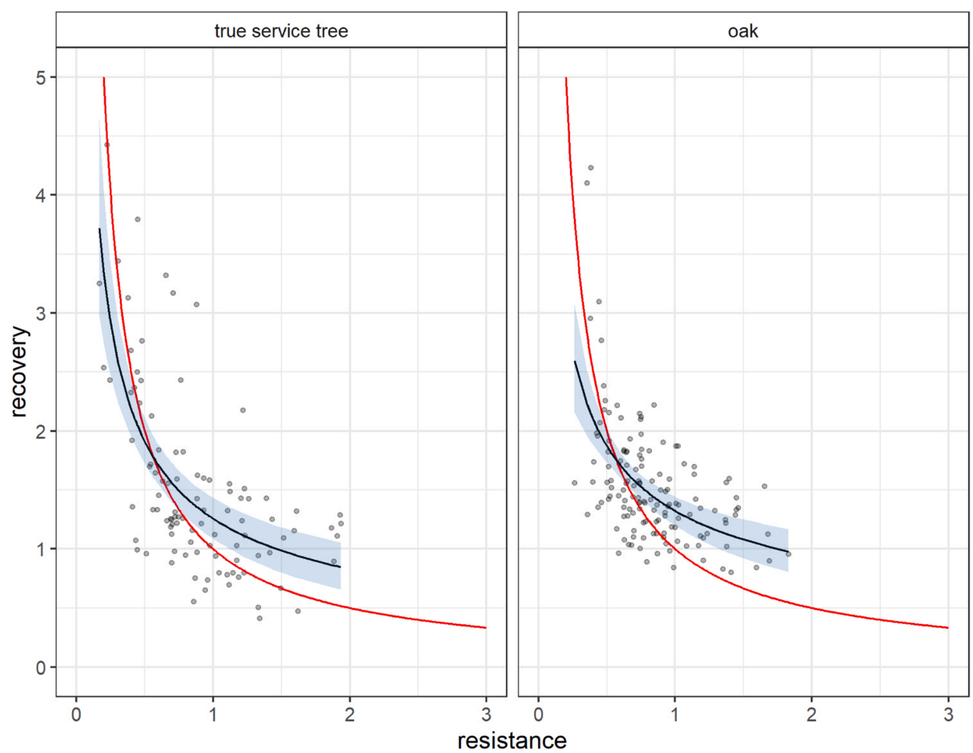

Fig. 8. Species-specific relationships between resistance and recovery. The black line with confidence bands calculated in a bootstrap with 1000 iterations. The red line represents the theoretical line of full resilience.

Graversgaard, 2013; Paganová et al., 2015), as observed for a tree in Slovakia. Turrientes et al. (2009) examined young true service trees in a dry climate (precipitation < 500 mm) and found a mean height of 2.3 m (min. 0.8 m, max. 4.7 m) and a mean diameter of 1.2 cm after 6 years. According to our allometric equations, a diameter of 1.2 cm results in a median height (0.5 quantile) of 2.99 m, for the 0.95 quantile 4.6 m and the 0.05 quantile 2.24 m. Especially for the 0.95 quantile, our model prediction were very close to their measurements, whereas our 0.05 quantile was clostest to their mean value. This can likely be attributed to the very dry conditions in Spain.

When comparing the allometric exponents to the ones of other rare native tree species, as studied by Schmucker et al. (2022), the allometric exponent of true service tree for the cpa-d ratio was generally higher than those for other rare species, expect for field maple (*Acer campestre* L.). True service tree was most similar to European hornbeam. Compared to the related wild service tree (*Sorbus torminalis* (L.) Crantz), we observed higher values for true service tree throughout all quantiles.

4.1.2. Stem taper and stem volume

The stem profiles derived from section diameters and tree-ring analysis indicate that open-grown true service tree may have a particular stem taper that differs from that of other tree species. When comparing the actual stem volume of the two trees in Copenhagen and Alnarp to total stem volume calculated by functions for other broadleaved tree species, we found that available functions substantially overestimated the stem volume of true service tree. The best matching function was one by Hillebrand (1998) for rowan (*Sorbus aucuparia* L.) which overestimated volume 'only' by to 33–35%. A function by Kahle (2004) for wild service tree overestimated volume by around 100%, and functions for European beech and pedunculate oak by Hagberg and Matérn (1975) and for oak by Petersen et al. (2003) (cf. Tarp-Johansen et al., 1997) overestimated by 30–79%. It should be cautioned, however, that these functions were not calibrated on trees with a dbh and height similar to those of our two true service trees, or such dbh-h combinations were on the edge of the calibration range. Moreover, open-grown trees, not least trees growing in a special environment such as in the city, may deviate in growth pattern and growth allocation from those within a forest. Nevertheless, our stem volume measurements indicate the potential need for a species-specific stem volume function for true service tree.

4.1.3. *Influence of competition and climate on crown size*

Our linear mixed model (Eq. 2) indicated that crowns in parks are larger than those in forests, all else being equal. This may be attributed to the negligible competition in parks throughout the entire lifetime of solitary trees, as also reflected by the Hegyi-index. Difficult growing conditions due to soil compaction or possible underground constructions did not seem to negatively influence true service tree. All trees in urban environments used in our study were growing in park-like conditions with some grass around them, and we did not include street trees growing in heavily sealed or paved soil.

We found no difference in crown size between oak and true service tree and no difference in the influence of competition between the two species. This corroborates our results from the quantile regression analysis. We therefore conclude that the growing space requirements, growth and competitive power of true service tree are similar to those of oak. Our study indicates that true service tree and oak are similar in sensitivity to competition from other trees. This corroborates the hypothesis that the low occurrence of true service tree is influenced by human activity to promote high forest systems and fast-growing coniferous species (Drapier, 1993; Kausch-Blecken von Schmeling, 2000; Skovsgaard and Graversgaard, 2013). However, we did not study the overall mortality of trees and the competition on moist sites. Our study was limited to relatively dry and warm regions, where other species are generally less competitive.

4.2. *Growth and drought stress response*

Due to the rarity of true service tree in cities, forests, and landscapes alike, the stem analysis of the felled true service tree in Copenhagen is rather unique. Even if we only have one sample tree, it gave us the unprecedented possibility of additional insight into the species' growth in an urban environment. The tree germinated around 1943, was planted at its permanent location in December 1948 and was cut in April 2022 at an age of approximately 80 years. As the tree was growing near a road and 350 m northwest of a power plant that was coal-fired until 1985, it was directly exposed to air pollution. Diameter increment, however, stayed stable over time. It only decreased during the last 10 years, possibly relating mainly to the inherent age decline. In line with these observations, Orlandi et al. (2022) found that the ability of true service tree to cope with air pollution is above average. Height growth culminated at the age of 20–22 years. Subsequently, it still increased, but at a lower rate. This may possibly be attributed to the species-specific growth characteristics of true service tree, as also indicated previously by Skovsgaard and Graversgaard (2013). Based on a simple model calibrated on empirical observations, they more specifically stated that the height development of true service tree is characterized by fast or even very fast growth in youth, followed by a gradual decline and later a final stagnation, much like the height development of oak. For oak, it is known that this decreased growth can continue steadily for a long time.

In our investigation, the long-term growth trend of true service tree could not be examined. Unfortunately, age determination for tree cores was impossible as we could not reach the pith of the trees that were cored. However, the diameter growth curves indicated a steady growth over multiple years. We observed similar growth patterns when comparing the dbh curves derived by the tree cores from oak. This indicates that oak and true service tree, in fact, share this characteristic of long-term, steady growth. Moreover, true service tree can grow to a very old age of several hundred years, similar to oak, again indicating similar growth patterns.

Overall, our results match the findings of other studies on true service tree. While we found the true service tree to be as drought tolerant as oak, Camarero et al. (2023) found it to be even more drought tolerant than Mediterranean oaks. In their study, true service tree had a better recovery after drought events and mainly so to short drought events between 2 and 7 months. Carried out in Spain, their study indicated that the growth of true service tree was influenced mainly by dry spring conditions. Apparently, the diameter growth of true service tree has a second peak in later summer, unlike oak. Therefore, the divergent results of the two studies may be attributed to differences in climatic conditions. Another study on tree rings of older trees (Kunz et al., 2018) did not suggest better drought tolerance of true service tree as compared to oak. However, combining the results of our study, covering locations both in Germany and Slovakia and one tree in Copenhagen, and the results of Camarero et al. (2023), covering locations in Spain, it is reasonable to conclude that in most cases, the drought tolerance of the true service tree and oak are similar. Furthermore, it is generally recognized that most species of *Sorbus* have a good drought tolerance (wild service tree: Kunz et al. (2018), Schmucker et al. (2023); rowan: Vogt (2001)). The similarity of growth patterns across all sites indicates the potential of true service tree to adapt to different climatic conditions. In light of climate change, planting of true service trees in urban areas and forests is a feasible option. However, due to the remaining uncertainty regarding the susceptibility to pathogens, and more specifically cankers and dieback due to *Neonectria ditissima*, cultivation should proceed with care.

Despite its rarity we managed to measure a large number of true service tree at different locations along a north-south gradient in Europe. To the best of our knowledge, our study is one of the most extensive empirically based analysis of the crown structure, growth and drought tolerance of true service tree so far.

5. Conclusions

True service tree's drought tolerance and overall growth behaviour are similar to those of oak. In contrast to common belief, as indicated in the literature, we could not identify a higher sensitivity to competition for true service tree than for nearby oak trees growing under similar conditions. In forest settings, we recommend managing true service tree based on guidelines for oak. In urban environments, height growth can be assessed based on nearby oak. The crown projection area of true service tree is, however, marginally larger than that of oak. Therefore, true service tree provides a correspondingly larger shading area than oak. Its growth characteristic, combined with its high drought tolerance make true service tree a promising admixed species in forests and urban environments. Due to its high susceptibility to fungal canker, we still recommend a limited cultivation. We highly encourage further research on pathology, especially with a focus on the influence of a changing climate on pathogens as well as on potential prevention methods. Furthermore, additional statistically designed field experiments under different climatic conditions are needed to study the influence of climate, other site conditions and management practices on the growth, distribution range and ecosystem services of true service tree.

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CRediT authorship contribution statement

JS: Investigation, Formal analysis, Methodology, Writing – original draft. **JPS:** Investigation, Writing – review & editing, Supervision. **EU:** Conceptualization, Supervision, Funding acquisition, Methodology, Writing – review & editing. **HP:** Conceptualization, Supervision, Methodology, Writing – review & editing.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2023.128161.

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