

How drought stress becomes visible upon detecting tree shape using terrestrial laser scanning (TLS)

Martin Jacobs^{*}, Andreas Rais, Hans Pretzsch

Chair of Forest Growth and Yield Science, TUM School of Life Sciences Weihenstephan, Technical University of Munich, Hans-Carl-v.-Carlowitz-Platz 2, 85354 Freising, Germany

ARTICLE INFO

Keywords:

Water retention experiment
Norway spruce
European beech
Allometry
Crown
Competition

ABSTRACT

Due to climate change, the occurrence of drought events with essential effects on trees will arise. The impact of severe drought stress on trees' vitality with regard to growth has often been analysed using traditional, easy-to-measure variables, such as diameter at breast height ($d_{1.3}$). Another commonly used tree-vitality indicator is crown transparency, which is not directly measurable and has to be determined qualitatively by well-trained field experts. In this study, we focused on tree dimensions, as potential vitality indicators, that are difficult to measure. The new approach for the efficient monitoring of tree vitality introduced here revealed three-dimensional change of tree shape due to drought stress.

The unique drought stress experiment "Kranzberg Forest Roof Experiment" (KROOF) was used as a basis for scanning and analysing the growth of Norway spruce (*Picea abies* (L.) H. Karst.) and European beech (*Fagus sylvatica* L.) under progressively limiting water reserves. Before the start of the experiment in the winter of 2012/2013, terrestrial laser scanning (TLS) was performed and repeated in the winter of 2018/2019. One sample of 21 trees was trenched and roofed (treatment), while additional 26 trees served as untreated reference (control). Using the TLS-point clouds of the two subsequent surveys, structural tree modifications within the 6-year period can be directly visualised, computed and linked to drought stress.

Drought stress led to significantly smaller crown size and lower height growth for both tree species. The crowns of Norway spruce trees increased significantly in transparency and roughness. In addition, high competition combined with drought stress significantly reduced the roughness and increased the compactness of the crown. The periodic annual change in crown projection area (pac_{cpa}) as well as the periodic annual height increment (pai_{height}) differed significantly between control and treatment for both tree species. Under drought conditions, pac_{cpa} changed by $-0.74 \text{ m}^2 \text{ yr}^{-1}$ and $-0.42 \text{ m}^2 \text{ yr}^{-1}$ for spruce and beech trees respectively, whereas the control trees showed a growth of $0.17 \text{ m}^2 \text{ yr}^{-1}$ and $0.62 \text{ m}^2 \text{ yr}^{-1}$ respectively. This means that crowns became considerably smaller under dry conditions. Under drought, the pai_{height} was 0.09 m yr^{-1} less for spruce and 0.17 m yr^{-1} less for beech compared with normal growing conditions. The periodic annual change in crown roughness ($pac_{roughness}$) was $-9.5\% \text{ yr}^{-1}$ if local competition increased by one.

Our results show that TLS can offer new opportunities for identifying structural features in trees. Iterative TLS-surveys may extend existing measuring campaigns on common long-term experimental plots, in order to analyse general changes or monitor tree vitality.

1. Introduction

Drought events will become more widespread, extensive and extreme in the future (IPCC 2012). Climate change is likely to accelerate tree mortality (Anderegg et al. 2013), where large trees may be potentially most vulnerable, putting crucial environmental, economic and social benefits at risk (Stovall et al. 2019). According to the rapid

environmental changes (IPCC 2012), the development and analysis of tree vitality indicators is important and should be continued in order to recognise tree stress at an early stage (Dobbertin et al. 2009). Here, we show innovative methods for the efficient monitoring of tree vitality under climate change, by way of example, for Norway spruce (*Picea abies* (L.) H. Karst) and the European beech (*Fagus sylvatica* L.).

There are a number of different indicators used to describe the

^{*} Corresponding author at: Chair of Forest Growth and Yield Science, Room: 1.2.2.10, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany.

E-mail address: martin.jacobs@tum.de (M. Jacobs).

vitality of an individual tree. The two most common ones are crown transparency, describing defoliation, and diameter growth of the individual tree (Dobbertin et al. 2009). In order to assess the long-term development of tree vitality, it is often necessary to select easy to measure indicators for forest inventories. Since a tree loses its needles or leaves before it dies, crown transparency has been recorded as an indicator of tree vitality by the percentage of a fully foliated tree crown (Müller and Stierlin 1990). To determine the growth of a tree, it has proven beneficial to measure the stem diameter at breast height ($d_{1.3}$) or the width of tree rings. Much more difficult to measure are tree height, branch and leaf growth, including the total aboveground biomass. For this reason, stem growth was primarily selected as an indicator of stress in general (Dobbertin 2005). According to Dobbertin et al. (2009), the traditional indicators crown transparency and stem growth could, with certain limitations, be used as indicators for the vitality of a single tree. However, they should not be considered on their own, as this could lead to misinterpretations. There is no universal indicator for the vitality of a single tree (Dobbertin et al. 2009). Therefore, research on traditional and potential tree vitality indicators is important to detect drought stress.

The growth of Norway spruce and European beech, which are the most common commercial conifer and broadleaved tree species in Germany (BMEL - Bundesministerium für Ernährung und Landwirtschaft 2014), has been adversely affected by recent drought events (Pretzsch et al. 2020a). In the drought of 2015, stand growth of Norway spruce decreased by approximately 30% (Pretzsch et al. 2020a). In general, stem increment in Norway spruce has been reduced by high summer temperatures (Seidling et al. 2012). In contrast, European beech has proven to be more drought-resistant in terms of growth (Pretzsch et al. 2018) and to recover better after wetter summers (Seidling et al. 2012). It can generally be assumed that more favourable growth conditions will promote growth at the lower part of the stem, while upper stem regions will grow proportionally better when resources are limited (Larson 1963). Accordingly, the majority of studies have shown that radial growth at breast height is more sensitive to climate-induced growth reductions compared to radial increment measured higher up the stem (Mette et al. 2015). Sterba (1996) showed that stress-induced tree growth declines is more pronounced at the lower third of the stem for softwood species such as Norway spruce, Scots pine (*Pinus sylvestris* L.) and silver fir (*Abies alba* Mill.). Similar growth patterns were observed for Norway spruce under drought stress (Sohn et al. 2012) and even under ozone stress (Pretzsch et al. 2010).

Height growth has been found to respond to severe drought stress even more sensitive than basal area growth (Rais et al. 2014) and should therefore be considered as an indicator of drought stress in future surveys. The behaviour of height growth under drought stress has rarely been investigated on mature trees (Mäkinen 1998; Wang et al. 2012), as the direct and accurate height measurement requires tree felling, which is often not feasible (Hasenauer and Monserud 1997). From an ecophysiological point of view, the height growth of most coniferous species is a complex multi-seasonal process involving the formation of terminal buds during late summer of the first year, and shoot elongation during spring in the second year (Bréda et al. 2006). In contrast, radial growth is primarily driven by current growing season precipitation (Griesbauer and Green 2010) and more precisely by the occurrence of water availability (Taeger et al. 2013).

The effects of drought stress on tree crown development have thoroughly been described by Bréda et al. (2006): If a tree's water supply deteriorates, the water pressure drops. This leads to constraints of water transport from the roots to the crown leaves. In order to prevent a drop in pressure and further drying out, trees close the stomata of their leaves to avoid water losses (McDowell and Sevanto 2010). When stomata are closed, less carbon dioxide can be absorbed, leading to a loss of productive photosynthesis needed for nutrition supply. The crowns of European beech and Norway spruce trees have been observed to be more transparent in hot compared with averagely hot summers (Seidling et al.

2012). The defoliation caused by drought can be reversed when the water supply improves (Eilmann et al. 2013). Dry and warm summers accelerate defoliation, discolouration of foliage, cone formation and mortality. High crown transparency can occur due to increased needle-shedding in the autumn after dry summers (Solberg 2004).

In terms of the impact of drought on crown size, it has been controversially discussed whether branch shedding can be seen acclimatisation to drought stress or not. In this context, Rood et al. (2000) assumed that the susceptibility to cavitation and the death of branches are physiologically linked to each other. In addition, the active process of shedding branches (cladogenesis) enables trees to adjust root-shoot ratios after drought-induced decline in root system extent and efficiency. In line with this natural process of cladogenesis, Bréda et al. (2006) hypothesised that crown thinning and branch shedding could be an acclimatisation to drought stress. In contrast, Rust and Roloff (2004) did not support the widely held assumption that cladogenesis is an immediate reaction to drought stress that reduces transpiring leaf area. Whereas branch shedding and dying was observed for oak, birch and poplar (Rood et al. 2000; Rust and Roloff 2002), evidence regarding this phenomenon is still lacking for the Norway spruce and European beech. Yet, it has not been validated that limited water availability shrinks the crown size, expressed as the crown projection area (*cpa*). In addition, it is not clear if the assumed effects of branch shedding and dying reach an extent, which is measurable via the *cpa*.

Most of the studies regarding drought stress reactions e.g. Bréda et al. (2006) either analysed past drought events (e.g. 2015) or simulated drought stress, to simulate more severe, potential future weather conditions, some studies have been conducted in regions where current weather conditions are assumed to be similar to future conditions in the region of interest. The unique experiment "KROOF" ("Kranzberg Forest Roof Experiment") has been the basis of several previous studies. It has served as a long-term ozone-fumigation experiment (Pretzsch et al. 2010) and as a drought-related intraspecific growth experiment (Pretzsch et al. 2018; Schäfer et al. 2019; Pretzsch et al. 2020b). From 2014 to 2018, the experiment aimed to investigate the effects of recurrent summer droughts on mature Norway spruce and European beech growing in monoculture and mixed-species stands. For this reason, novel precipitation-exclusion roofs were constructed over six of 12 plots, in order to exclude any summer precipitation on the precipitation-exclusion plots. Based on this drought experiment from 2014 to 2018, Pretzsch et al. (2020) stated that the induced water limitation led to a decline in growth in the first year, especially for Norway spruce. A slight acclimatisation to the dry conditions followed. Beech acclimatised and recovered faster than spruce under all growing conditions, while spruce only acclimatised faster in mixture with beech. Both species showed a higher mortality under induced drought compared to the control plots; for spruce, the long-term mortality rate was higher than for beech. Our current investigation is directly linked to this research and concentrated on tree dimensions, which have so far been difficult to measure and thus have not yet been analysed.

Based on terrestrial laser scanning (TLS), the current study focused on the scan and quantification of the variability in stem and crown characteristics caused by drought stress. TLS can measure detailed stand and individual tree information (Trochta et al. 2017) and is a suitable tool for measuring physical crown dimensions (Seidel et al. 2015), without the need for cutting of trees or time-consuming and costly manual surveys. When for instance, TLS derived tree heights and traditional measured heights have been compared with true tree heights using destructive techniques TLS was found to be more accurate (Calders et al. 2015; Jacobs et al. 2020). Our study focused on stem taper as the stem-form-describing variable, and total tree height as the height-describing variable. Regarding crown characteristics, *cpa*, crown transparency and crown roughness were considered. The study addressed the following research questions:

Q1 How does severe drought stress affect stem characteristics ($d_{1.3}$, height, taper)?

Table 1

Site, plot and tree characteristics of the experimental plot Kranzberger Forst FRE 813/1 are given for 2014, i.e. before the start of the throughfall exclusion recorded manually.

Location					
Altitude above sea level	m	490			
Coordinates		11°39'42"E, 48°25'12"N			
Climate¹⁾					
Mean annual temperature	°C	7.5			
Annual precipitation	mm yr ⁻¹	750–800			
Soil					
Initial substrate		Loess			
Soil type		Luvisol			
Trees²⁾					
Species		European beech		Norway spruce	
Group		Control	Treatment	Control	Treatment
Trees per group and species		13	11	13	10
Stand density index <i>SDI</i>		851 (44)	823 (43)	777 (73)	816 (35)
Diameter at breast height <i>d</i> _{1.3}	cm	32.5 (8.7)	30.9 (7.4)	35.9 (5.6)	37.7 (9.5)
Height <i>h</i>	m	29.3 (1.6)	29.2 (3.1)	31.8 (2.1)	31.6 (2.0)
Crown radius <i>cr</i>	m	3.1 (1.1)	3.3 (1.3)	2.3 (0.4)	2.4 (0.2)
Crown base height <i>cbh</i>	m	16.7 (3.6)	16.5 (2.4)	16.5 (4.8)	17.4 (4.3)
Crown projection area <i>cpa</i>	m ²	33.4 (26.6)	39.0 (33.1)	16.6 (5.8)	18.0 (2.6)

1) Climate reference period 1988–2017.

2) Data from the survey in 2014, mean (±SE)

Q2 How does severe drought stress affect crown characteristics (*cpa*, transparency, roughness)?

Q3 How does the interaction of severe drought stress and competition affect tree allometry (*d*_{1.3}, *cpa*)?

2. Material and methods

2.1. Material

The experimental plot Kranzberger Forst (FRE 813/1) with a size of 0.5 ha is located in the southern part of Bavaria, approximately 35 km northeast of Munich. On this site, the “Kranzberg Roof Project” (“KROOF”) was initiated in spring 2013 (Pretzsch et al. 2014). Table 1 summarises relevant site and plot characteristics.

The plot was specially selected for the KROOF experiment (Pretzsch et al. 2014). The mixed stand consists of European beech and Norway spruce, was never thinned and is fully stocked. Both tree species share the same soil resources and form a common closed canopy. Within the site, large groups of beech grow surrounded by spruce. In 2014, tree age within the mixed stand was assessed to be 63 ± 2 years for spruce and 83 ± 4 years for beech (Pretzsch et al. 2016). The conditions such as growth stage, stand density, basal area, or stem volume of mono-specific spruce, monospecific beech, and beech/spruce mixture are similar across the control and treatment plots each (Pretzsch et al. 2014).

In 2013, the experimental area was subdivided into six groups that were not roofed (“Control”) and six groups that were roofed (“Treatment”). Each plot had four to six beech trees on one side and the same number of spruce trees on the opposite side, enabling a broad contact zone in between the two. Plot sizes ranged between 110 m² and 200 m², amounting to 868 m² and 862 m² in total for control and drought treatments, respectively (Pretzsch et al. 2016). On treatment plots, special houses were installed underneath the canopy three metres above the ground. The roof of each house automatically closes during rainfall. During the construction process, the forest floor was covered with wooden pallets, to avoid compaction of the soil from construction work (Grams et al. 2020). Vegetation cover at the forest floor was almost entirely absent due to the high density of the tree crowns. Each roof extends approximately 40 cm beyond the borders of the treatment plots to prevent throughfall (Grams et al. 2020). The novelty of the roof construction is the automated closure during rain by means of water impermeable, tile-composed roller blinds, which are electrically motorised (Pretzsch et al. 2014). The roof-intercepted quantities of water are channelled out of the study site. This design prevents a

greenhouse effect when there is no rain. The stationary portions of the roof are secured around individual trees and permanently closed. Stem flow is negated via perforation hoses encircling each tree stem above the roof, and the thus-collected water directed to the roof gutters (Grams et al. 2020). All rain that is held off is transported off the experimental site via plastic hoses attached to gutters at each side of the roofs. Additionally, the roofed plots are hydraulically isolated to avoid lateral soil water access. Hence, a durable cover, preventing penetration by water or roots, is placed in the dug trenches around the roofed plots. In 2010, the 12 experimental plots were trenched to 1 m soil depth, where the layer of sandy loam hardly allows deeper root growth. As such preparation causes root injury, trenching was performed four years before the actual beginning of the drought experiment (Pretzsch et al. 2016). It was possible to concentrate on the effects of experimentally induced drought without the interference of other limiting factors, due to the good water and nutrient supply along with the high-water storage capacity of the soil. The drought phase of the KROOF experiment started in March 2014 and continued until November 2018. During this phase, the roofs were automatically closed during rainfall in the growing season and on average withheld $69 \pm 7\%$ of the annual rainfall (Grams et al. 2020). The water was kept away in summer, whilst in winter the forest ecosystem of the treated plots was allowed to recover.

An overview of classical growth and yield related variables of all scanned sample trees is provided in Table 1. More detailed information on the experimental design can be found in Pretzsch et al. (2014), Goisser et al. (2016) and Grams et al. (2020).

2.2. Methods

2.2.1. Scan acquisition

In winter 2012/2013, before the start of the drought stress experiment, terrestrial laser scanning (TLS) was carried out and repeated in the winter of 2018/2019. Using the TLS-point clouds from the two surveys, structural tree modifications within the six-year period were directly visualised, computed and linked to water limitation. Two different laser-scanning systems were used for the two surveys: RIEGL LMS-Z420i (RIEGL 2010) for the winter of 2012/2013 and RIEGL VZ-400i (RIEGL 2019) for the winter of 2018/2019. A detailed description of the scan acquisition can be found in the appendix.

2.2.2. Tree characteristics

Several tree characteristics, describing both stem and crown properties, were extracted from the TLS data. Only the measurements for *d*_{1.3}

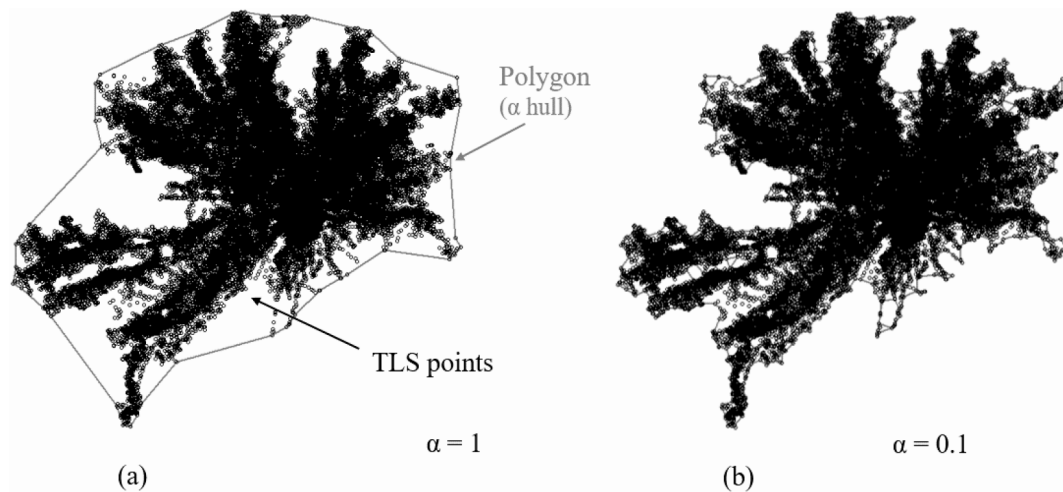


Fig. 1. Top view of tree number 89, by way of illustration of the different methods for calculating the crown projection area within the R package “alphahull”. Choosing an α -value of 1 (a), a projection area similar to the traditional crown projection area was derived. Choosing an α -value of 0.1 (b), the polygon framed the crown tightly. The crown transparency was calculated based on both crown projection areas.

were taken manually with a girth tape. The isolation of the single tree from the TLS point cloud was performed using a pre-processing algorithm within the R programming environment (R Core Team 2016). After this step, each tree was visually checked for completeness. If necessary, unrecognised tree parts were added manually, and artefacts, not belonging to the tree, removed using the software RiSCAN PRO version 2.0.2 (<http://www.riegl.com/products/software-packages/ri-scan-pro/>).

Stem properties – diameter, height and taper

The diameter at breast height $d_{1.3}$ was measured for all trees, using a girth tape, in the winter of 2012/2013 and winter of 2018/2019. The periodic annual diameter increment ($pa_{d_{1.3}}$ in cm yr^{-1}) was calculated as the difference between the two dates divided by the time range of six years. Based on the TLS data, tree height was calculated as the difference between the highest and lowest Z-axis point of the isolated tree. The periodic annual height increment (pa_{height} in m yr^{-1}) was computed as the difference between the heights from the two consecutive surveys, divided by six years. Generally, taper is the diameter change per unit of length. Modern log measurement systems determine the taper as the slope of a linear regression between different diameters and their axial positions (ÖNORM L 1021 2013). The procedure applied here was as follows: Firstly, the stem was isolated from the TLS-data using the method developed in Jacobs et al. (2020). Secondly, the stem was separated into 0.1 m intervals, from 1.3 m to 10.0 m. Thirdly, within this stem section, the taper was calculated as the slope of the linear regression between diameter and axial position. Finally, the periodic annual taper change (pac_{taper} in $\text{mm m}^{-1} \text{yr}^{-1}$) was the difference between the taper in the winter of 2012/2013 and in the winter of 2018/2019, divided by six years.

Crown properties – projection area, transparency and roughness

Based on the point clouds from TLS scanning, the crown properties were calculated using the R package “alphahull” (Rodriguez-Casal and Pateiro-Lopez 2019). This package enabled the determination of the area and bordering line of a sample of points in a plane and was successfully used to analyse the crown structure (Rais et al. 2020). By varying the α -value, the tightness of the bordering line around the point cloud could be adjusted. Very low α -values even recognise areas without any points in the middle of a two-dimensional point set.

Choosing an α -value of 1, the TLS points were framed with a slack polygon (Fig. 1a). The area inside this polygon was used as a proxy to the crown projection area ($cpa_{tradition}$), which closely resembles the traditional crown projection area that is recorded in the field from the ground. Subtracting the two subsequent crown projection areas from

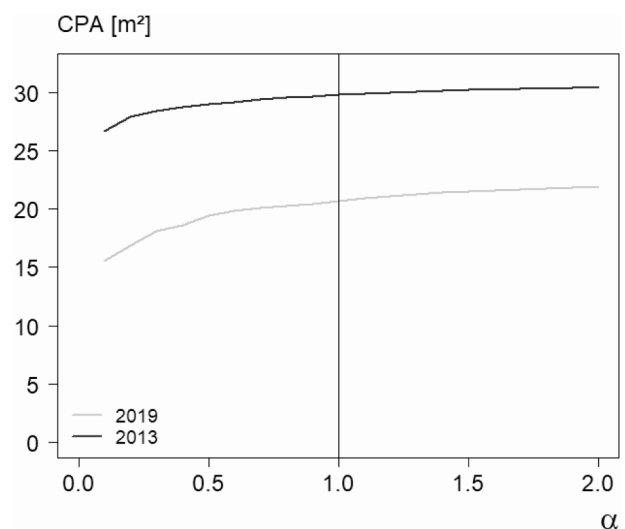


Fig. 2. Comparison of different α -values for α hulls determining the cpa of tree number 89.

each other and then dividing the difference by six years, we obtained the periodic annual change of the crown projection area (pac_{cpa} in $\text{m}^2 \text{yr}^{-1}$). Without claiming to have calculated the actual $cpa_{tradition}$, it was important to choose the same alpha values for the scans of winter 2012/13 and winter 2018/19, to ensure the comparability of the two measurements (*ceteris paribus* conditions).

The crown projection area (Fig. 1a) also served to assess the crown transparency. For this, a polygon was created surrounding the two-dimensional point cloud per tree, choosing an α -value of 0.1. Consequently, the polygon fitted tightly to the points (Fig. 1b). The resulting area of the tight polygon (Fig. 3) was normalised by the $cpa_{tradition}$ first and then subtracted by 1. Analogous to the previous definitions, the difference in the crown transparencies on two different dates were divided by six years to obtain the periodic annual change in crown transparency ($pac_{transparency}$ in $\% \text{yr}^{-1}$). The calculated crown transparency is not the replication of the conventionally calculated parameter (Müller and Stierlin 1990). Our calculation is based on the two-dimensional top view perspective whereas the conventional crown transparency is estimated based on lateral perspectives.

The tight polygon ($\alpha = 0.1$, Fig. 1b) can be used not only for the

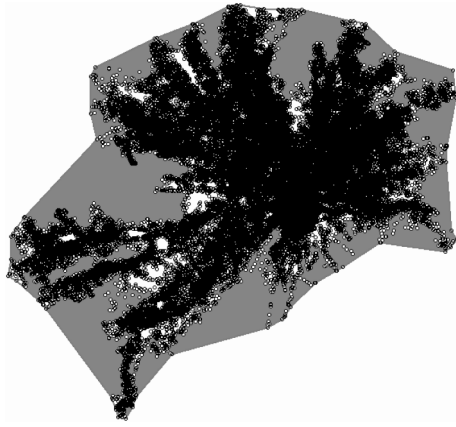


Fig. 3. Two-dimensional bird's-eye view of a Norway spruce tree number 89 scanned with TLS in winter 2012/13. The grey area shows what we considered to be the transparent parts of the crown projection area.

derivation of an area, but also of the polygon length to determine the crown roughness. To eliminate the size effect, we first calculated the perimeter of a circle, which had the same area as the polygon of *cpa*-tradition ($\alpha = 1$, Fig. 1a). The perimeter of the tight polygon ($\alpha = 0.1$, Fig. 1b) was finally divided by the perimeter of the circle (Eq. (1)). By analogy with the previous definitions, the difference in the crown roughness on two different dates was divided by six years, to obtain the periodic annual change of crown roughness (*pac_{roughness}* in % yr⁻¹).

$$pac_{roughness} = \frac{\left(\frac{P_{length_{cpa0.1}}}{2 \cdot \sqrt{cpa_{tradition0.1} \cdot \pi}} \right)_{2018/19} - \left(\frac{P_{length_{cpa0.1}}}{2 \cdot \sqrt{cpa_{tradition0.1} \cdot \pi}} \right)_{2012/13}}{6} \quad (1)$$

pac_{roughness} = periodic annual change of crown roughness

P = Polygon

cpa = crown projection area

α = alpha-values

The *cpa* varies with different α -values but at value 1 the difference in *cpa* between the two measurements was stable (Fig. 2).

Finally, we looked at the investment pattern between stem and crown. The allometry exponent β of the allometric Eq. (2) was determined. The slope β indicated the change in *cpa* at the growth rate of the *d_{1.3}* (von Bertalanffy 1951). If $\beta > 1$, a positive allometry is present, where *cpa* changes more than *d_{1.3}*. Vice versa, with negative allometry ($\beta < 1$), *d_{1.3}* changes more than *cpa*. Isometry prevails if the initial proportions remain constant over time (Pretzsch 2001)

$$\ln(cpa) = t + \beta_{cpa,d1.3} \times \ln(d_{1.3}) \quad (2)$$

cpa = crown projection area

d_{1.3} = diameter at breast height

t = offset

$\beta_{cpa,d1.3}$ = allometry exponent

Competition

The competition was expressed by the index introduced by Hegyi (1974), using Eq. (3). The original Hegyi-index forms the ratio between the diameters of neighbouring trees and the reference tree, considering concurrently the distance from all the competitors. The spatial positions of all trees were taken from the terrestrial laser scans.

$$HgCI_i = \sum_{j=1}^n \frac{d_{1.3j}}{d_{1.3i}} \frac{1}{Dist_{ij}} \quad (3)$$

In this formula *HgCI_i* is the competitor index for reference tree *i*, *d_{1.3j}* is the *d_{1.3}* of competitor tree *j* (cm), *d_{1.3i}* the *d_{1.3}* of reference tree (cm), *Dist_{ij}* the distance between reference tree *i* and competitor tree *j*

Table 2

LMM Functions regarding Q1, Q2 and Q3. The *pai_{d1.3}* (cm yr⁻¹) is the periodic annual diameter at breast height increment, *pai_{height}* (m yr⁻¹) is the periodic annual total tree height increment, *pac_{taper}* (yr⁻¹) the periodic annual change of taper, *pac_{cpa}* (m² yr⁻¹) the periodic annual change of crown projection area, *pac_{transparency}* (% yr⁻¹) the periodic annual change of crown transparency, *pac_{roughness}* (% yr⁻¹) the periodic annual change of crown roughness, $\beta_{cpa,d1.3}$ the tree allometry exponent.

	Response variable	Linear predictors	Interaction effects	Function
Q1:	<i>pai_{d1.3}</i>			(5)
	<i>pai_{height}</i>			(6)
	<i>pac_{taper}</i>	Species	Drought	(7)
Q2:	<i>pac_{cpa}</i>	Drought	Competition	(8)
	<i>pac_{transparency}</i>	Competition		(9)
	<i>pac_{roughness}</i>			(10)
Q3:	$\beta_{cpa,d1.3}$			(11)

(m), and *n* the number of competitor trees.

The competition zone radius (CZR) proposed by Lee and von Gadow (1997), defined as the radius in which competitors were searched around the reference tree (Eq. (4)), is a function of the number of trees per hectare (*N*), and was determined only once, so that the radius was the same for every investigated tree. The competition zone of border trees was mostly outside the plot in relative size. To counteract this problem, we extrapolated the calculated competition for the partial area inside the plot to the total area of the competition zone.

$$CZR = k \cdot \sqrt{\frac{10000}{N}} \quad (4)$$

The variable *k* is a constant defining the radius of the competition zone ($2 < k < 4$) and *N* the number of trees per hectare (Lee and von Gadow 1997).

2.2.3. Evaluation

T-test

To visualise possible differences between control and treatment plots regarding drought stress, we created boxplots for all analysed parameters. A *t*-test was used to determine whether there is a significant difference between the means of the two groups: The control group (no water limitation) and the treatment group (water limitation).

Mixed effect regression model

The data was nested at the group level, which means that there were several trees in one group. Therefore, a mixed effect regression model with random effects at plot level was required. We started with a complex model using a generalized mixed-effects model (GAMM) with smoother expecting a non-linear relationship between the interaction of drought and competition. Instead, the relationship turned out to be linear. Thus, we used a linear mixed-effects model (LMM). We formulated seven LMM functions to answer Q1 regarding the stem property parameters (Function 5 to 7), Q2 regarding crown property parameters (Function 8 to 10) and Q3 regarding their allometry exponent (Function 11). All parameters were set as response variables to analyse the effects of species, drought, competition and the interaction effects between competition and drought (Table 2). All models explain the response variable as a function of different linear predictors like drought, species and competition. Here is the general structure of the model we used for all LMM functions:

$$Y_{ij} = a_0 + a_1 * X_{1,i} + a_2 * X_{2,j} + a_3 * X_{3,j} + a_4 * X_{2,ij} * X_{3,ij} + b_j + \varepsilon_{ij}$$

Throughout each model, the variable *Y* is the response variable, the variables *X₁*...*X₃* (*X₁* = Species, *X₂* = Drought and *X₃* = Competition) are the linear predictors, the variable *i* indexes the tree, and the variable *j* the plot. The variable *a₀* represents the model's intercept, the variables *a₁*...*a₄* represent the slope coefficients, the variable *b* represents the random effect related to the plots and the symbol ε represents the

Table 3

Overview of *t*-test statistics. Mean, standard deviation (in brackets) and *p*-value are given. The $pai_{d1.3}$ (cm yr^{-1}) is the periodic annual diameter at breast height increment, pai_{height} (m yr^{-1}) is the periodic annual total tree height increment, pac_{taper} ($\text{mm m}^{-1} \text{yr}^{-1}$) the periodic annual change of taper, pac_{cpa} ($\text{m}^2 \text{yr}^{-1}$) the periodic annual change of crown projection area, $pac_{transparency}$ ($\% \text{yr}^{-1}$) the periodic annual change of crown transparency, $pac_{roughness}$ ($\% \text{yr}^{-1}$) the periodic annual change of crown roughness, $\beta_{cpa,d1.3}$ the tree allometry exponent.

	European beech			Norway spruce		
	Control	Treatment	<i>p</i> -value	Control	Treatment	<i>p</i> -value
$pai_{d1.3}$	0.22 (0.16)	0.11 (0.08)	0.049	0.26 (0.13)	0.14 (0.08)	0.011
pai_{height}	0.36 (0.09)	0.19 (0.08)	0.000	0.25 (0.12)	0.16 (0.04)	0.019
pac_{taper}	-0.05 (0.04)	-0.07 (0.07)	0.472	-0.06 (0.05)	-0.1 (0.14)	0.560
pac_{cpa}	0.62 (0.53)	-0.42 (0.52)	0.000	0.17 (0.29)	-0.74 (0.51)	0.000
$pac_{transparency}$	0.7 (1.02)	1.27 (0.95)	0.168	0.55 (0.92)	1.67 (0.89)	0.008
$pac_{roughness}$	6.18 (7)	13.61 (15)	0.154	2.11 (4.2)	6.35 (3.68)	0.018
$\beta_{cpa,d1.3}$	4.26 (25.3)	-10.0 (16.8)	0.113	-0.06 (5.5)	-15.68 (11.4)	0.002
Trees per group and species	13	11		13	10	

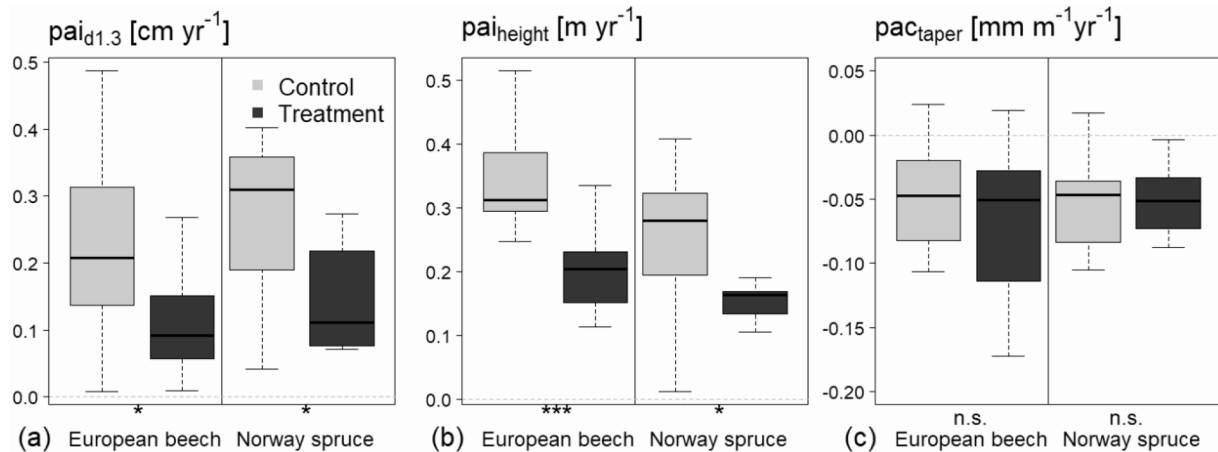


Fig. 4. Effects of drought stress on stem properties Q1, (a) $pai_{d1.3}$ periodic annual $d_{1.3}$ increment in cm yr^{-1} , (b) pai_{height} periodic annual height increment in m yr^{-1} , (c) pac_{taper} periodic annual change of taper in $\text{mm m}^{-1} \text{yr}^{-1}$, yr is the year. Significance values: '***' $p < 0.001$, '**' $p < 0.01$, '*' $p < 0.05$, 'n.s.' not significant.

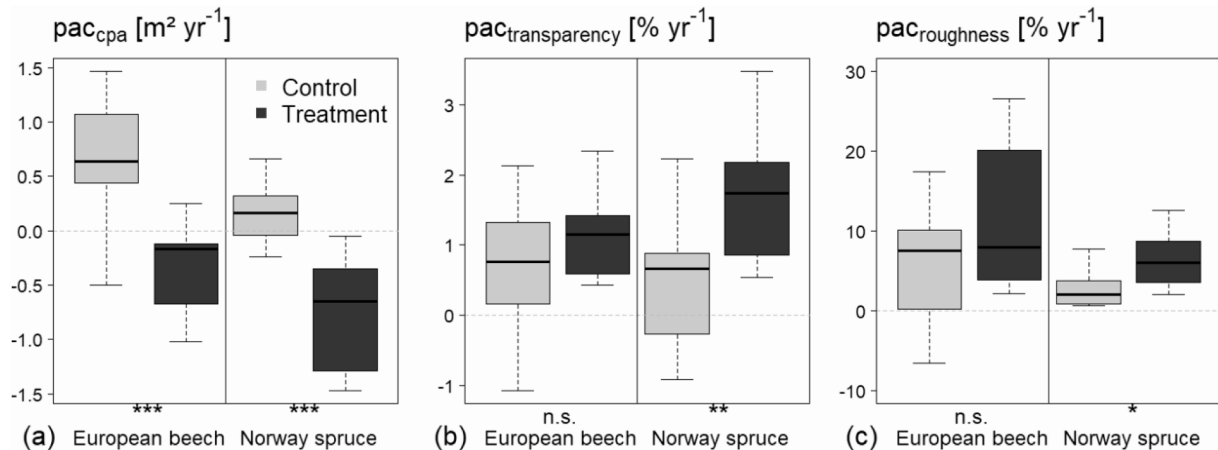


Fig. 5. Effects of drought stress on crown properties Q2, (a) pac_{cpa} the periodic annual change of cpa in $\text{m}^2 \text{yr}^{-1}$, (b) $pac_{transparency}$ the periodic annual change of crown transparency in $\% \text{yr}^{-1}$, (c) $pac_{roughness}$ the periodic annual change of crown roughness in $\% \text{yr}^{-1}$. The variable cpa is the crown projection area (m^2) and yr is year. Significance values: '***' $p < 0.001$, '**' $p < 0.01$, '*' $p < 0.05$, 'n.s.' not significant.

remaining errors.

Whether the *t*-test or the mixed effect regression model, the significance level for our tests is considered statistically significant when the *p*-value was lower than 5%. The processing was performed within the programming environment of R (R Core Team 2016). The R packages used for the evaluation were stats and graphics, which are both part of R (R Core Team 2016). Zuur et al. (2009) described the technical details (mgcv package (Wood 2017)).

3. Results

An Overview of the *t*-test statistics is provided in Table 3. The $pai_{d1.3}$ and pai_{height} differ between control and treatment for both tree species (Fig. 4ab, Table 3). In contrast to the control trees, which show growth in $pai_{d1.3}$ of 0.26 cm yr^{-1} for spruce and 0.22 cm yr^{-1} for beech, the treated trees have a lower growth of 0.14 cm yr^{-1} for spruce and 0.11 cm yr^{-1} for beech (Table 3). The pai_{height} of the control trees is

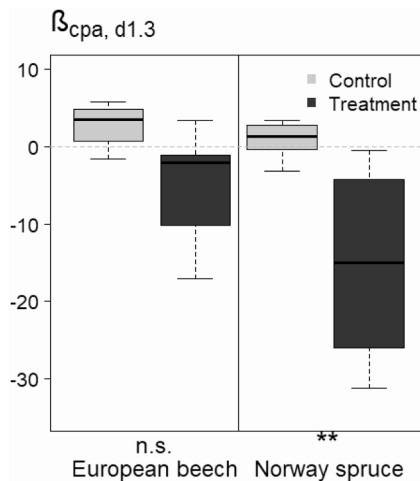


Fig. 6. Effects of drought stress on the allometry exponent $\beta_{cpa,d1.3}$ Q3. Significance values: ‘****’ $p < 0.001$, ‘***’ $p < 0.01$, ‘**’ $p < 0.05$, ‘n.s.’ not significant.

0.25 m yr⁻¹ for spruce and 0.36 m yr⁻¹ for beech, while the treated spruces (0.16 m yr⁻¹) and beeches (0.19 m yr⁻¹) had lower growth (Table 3).

The pac_{taper} (Fig. 4c, Table 3) does not differ between control and treatment. In contrast to the control trees, which show taper on average by $-0.063 \text{ mm m}^{-1} \text{ yr}^{-1}$ for spruce and $-0.049 \text{ mm m}^{-1} \text{ yr}^{-1}$ for beech, the taper of the treated trees decreased on average by $-0.095 \text{ mm m}^{-1} \text{ yr}^{-1}$ and $-0.07 \text{ mm m}^{-1} \text{ yr}^{-1}$ respectively (Table 3).

The crown properties pac_{cpa} , $pac_{transparency}$ and $pac_{roughness}$ are affected by drought stress especially for spruce (Fig. 5abc, Table 3). The crown property pac_{cpa} differs highly significant between control and treatment for both tree species (Fig. 5a, Table 3). The control trees showed growth in pac_{cpa} by $0.17 \text{ m}^2 \text{ yr}^{-1}$ for spruce and $0.62 \text{ m}^2 \text{ yr}^{-1}$ for beech, while the pac_{cpa} of the treated trees changed by $-0.74 \text{ m}^2 \text{ yr}^{-1}$ for spruce and $-0.42 \text{ m}^2 \text{ yr}^{-1}$ for beech (Table 3).

The $pac_{transparency}$ (Fig. 5b, Table 3) and $pac_{roughness}$ (Fig. 5c, Table 3) differ between control and treatment only for Norway spruce trees. In contrast to the control trees, which show an increment in $pac_{transparency}$ of $0.55\% \text{ yr}^{-1}$ for spruce and $0.7\% \text{ yr}^{-1}$ for beech, the $pac_{transparency}$ of the treated trees increased by $1.67\% \text{ yr}^{-1}$ for spruce and $1.27\% \text{ yr}^{-1}$ for beech (Table 3). The $pac_{roughness}$ increased by $2.11\% \text{ yr}^{-1}$ for spruce and $6.18\% \text{ yr}^{-1}$ for beech, while the $pac_{roughness}$ of the treated trees increased by $6.35\% \text{ yr}^{-1}$ for spruce and $13.61\% \text{ yr}^{-1}$ for beech (Table 3).

Table 4

LMM statistics for Q1, Q2 and Q3. Estimates and significance values are given. The $pai_{d1.3}$ (cm yr⁻¹) is the periodic annual diameter at breast height increment, pai_{height} (m yr⁻¹) is the periodic annual total tree height increment, pac_{taper} (mm m⁻¹ yr⁻¹) the periodic annual change of taper, pac_{cpa} (m² yr⁻¹) the periodic annual change of crown projection area, $pac_{transparency}$ (% yr⁻¹) the periodic annual change of crown transparency, $pac_{roughness}$ (% yr⁻¹) the periodic annual change of crown roughness, $\beta_{cpa,d1.3}$ the tree allometry exponent. Competition is the local index by Hegyi (1974). Within a given category of drought (control vs. treatment) and species (Norway spruce vs European beech), numbers within the same column are significantly different at the 0.05 probability level if they are different in all letters (a and b); linear mixed-effects model; R² (adjusted) is the coefficient of multiple determination; all significance values and trends were bold: ‘****’ $p < 0.001$, ‘***’ $p < 0.01$, ‘**’ $p < 0.05$.

Function	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Response variable	$pai_{d1.3}$	pai_{height}	pai_{taper}	pac_{cpa}	$pac_{transparency}$	$pac_{roughness}$	$B_{cpa,d1.3}$
Intercept	+0.34****	+0.29***	-0.07*	+0.55**	+0.58	+2.01	+6.63
Species							
Norway spruce	-a	-a	-a	-a	-a	-a	-a
European beech	+0.01b	+0.10b**	+0.04b	+0.52b***	-0.08b	+7.73b**	+7.7b
Drought							
Control	-a	-a	-a	-a	-a	-a	-a
Treatment	-0.12b	-0.14b*	-0.06b	-1.43b**	+1.2b	+15.9b*	-21.57b
Competition	-0.07**	-0.03	-0.005	-0.27**	+0.05	-1.16	-5.47
Drought:Competition							
Control	-a	-a	-a	-a	-a	-a	-a
Treatment	-0.02b	-0.003b	-0.08b	+0.3b	-0.3b	-9.5b*	+3.74
R ² (adjusted)	0.33	0.43	-0.03	0.61	0.1	0.25	0.16

The allometry exponent $\beta_{cpa,d1.3}$ changed under drought stress (Fig. 6, Table 3). The trend towards crown shrinking and lower growth under drought stress was seen in both tree species (Table 3). Whereas spruce changed its investment behaviour significantly under drought stress, the beech trees experienced the same trend, but the investment behaviour did not change.

Regarding Q1 and Q2, it can be observed that despite random effects on plot level, drought stress affected pai_{height} , pac_{cpa} and $pac_{roughness}$ regardless of the tree species (Table 5, Function 6, 8 and 10), which is demonstrated by the estimate values of -0.14 , -1.43 and $+15.9$ for treated trees respectively. Furthermore regarding Q3, the local competition had an effect on the $pai_{d1.3}$ and pac_{cpa} of the control trees (Table 4, Function 5 and 8), which is shown by the estimate values of -0.07 and -0.27 if competition increases by one unit respectively. The lower the competition, the higher was the growth in cpa and $d1.3$ for the control trees. The $pac_{roughness}$ is the only parameter that is affected by local competition under drought stress, which is demonstrated by the estimate value of -9.5 for treated trees if competition increases by one unit. The lower the competition, the higher the roughness of the crowns for trees under drought stress, and vice versa. In terms of species, the variables pai_{height} , pac_{cpa} and $pac_{roughness}$ differ (Table 5 Function 6, 8 and 10), which is demonstrated by the estimate values of $+0.10$, $+0.52$ and $+7.73$ respectively for beech trees.

4. Discussion

Drought stress led to a significantly smaller crown size as well as a lower stem and height growth. In addition, high competition combined with drought stress resulted in crowns that were less rough and thus more compact.

4.1. Tree shape modified by drought

Our results cannot prove an effect of drought stress on the stem form. Only a trend towards cylindrical stem forms occurred (Table 4, Function 7). Sohn et al. (2012) also did not find a combined effect of both drought and competition on radial growth along the stem. Our study showed that lower competition might have the potential to improve growth performance of trees in response to drought if the whole stem is considered (Table 4, Function 7). One reason for the non-significance may be the short time period or the small sample size ($N = 47$) of our study. Consequently, (relative) differences were probably reduced between roofed and control plots. Due to the low model performance (R^2), drought, species and local competition may not be the only root causes of the observed stem-form differences (Table 4, Function 7).

The height growth was affected by drought stress for each individual tree species and was lower in comparison to the control trees (Fig. 4b). In Table 4 (Function 6), the height growth was affected by drought, which is demonstrated by the estimate value of -0.14 for all treated trees. For the Douglas fir, height growth response to drought stress was observed to be an even more sensitive indicator than basal area (Rais et al. 2014). In the past, only a few drought related studies have focused on the height growth of mature trees, as the accurate measurement of height increments requires the felling of trees (Hasenauer and Monserud 1997). As well as the technical issue concerning measuring, the height growth of most species is a complex multi-seasonal process from an ecophysiological point of view (Bréda et al. 2006). Due to the observation of the experiment over six years and computing the annual mean increment, this difficulty was likely averaged out.

Drought stress led to a significantly smaller crown size for each individual tree species (Fig. 5a). In Table 4 (Function 5), this is demonstrated by the estimate value of -1.43 for all treated trees. The crowns of Norway spruce trees also increased in transparency and roughness on the treatment plots (Fig. 5bc). The TLS scans were performed after the vegetation period and thus beech trees had no leaves. The lower crown transparency for beech trees could only have arisen from a loss of branches. Overall, almost all trees become more transparent, with trees under drought stress showing crowns that are more transparent (Fig. 5b). This could be related to actual drought years such as 2015, when control trees also suffered from drought stress.

4.2. Acclimatisation strategies to deal with drought stress and competition

The impact of drought on the crown has been critically discussed and assumptions regarding all strategies vis-à-vis drought were summarised in the review by (Bréda et al. 2006). These potential acclimatisation strategies were cavitation and cladoptosis. Due to drought-induced branch die-off, fewer branches lose water through transpiration, which enables the remaining shoots to maintain a favourable water balance, although resulting in smaller and more transparent crowns (Rood et al. 2000). In addition to the die-off of branches, there is also the deliberate, active process of shedding branches (cladoptosis). This mechanism enables trees to adjust root-shoot ratios after drought-induced decline in root system extent and efficiency. Branch shedding and dying was observed for oak, birch and poplar (Rood et al. 2000; Rust and Roloff 2002). In both two hypotheses of acclimatisation strategies, crown size should get smaller due to drought stress. Our scans were performed in winter, when beech trees were free of foliage. Using the *cpa* as a rather simple crown attribute, we were able to prove significant crown shrinkage per year, which was observed over a time span of only six years. Hence, the fact that drought led not only to losses in needles, can be seen from the significantly smaller non-leaved crowns of beech trees. They may have suffered from drought stress and shed parts of their branches. The assumed effects of branch shedding and dying reached an extent that was measurable in terms of *cpa*, crown transparency and crown roughness using TLS. No other study has previously been able to confirm these results. The theories and assumptions about drought stress reactions (Bréda et al. 2006) have thereby been confirmed, and been clearly demonstrated by the use of TLS.

Trees that are experiencing low levels of competition tend to increase their crown width (Forrester et al. 2013). This is confirmed by our study for all trees (Table 4, Function 8), which is demonstrated by the estimate value of -0.23 if competition increases by one unit. During drought, the competition had no influence on the *cpa*, and this is also the case for the crown transparency (Table 4, Function 9). We assume that the control trees are mainly light-limited, and therefore react more strongly to above ground competition from neighbours than those trees that are

water-limited due to water retention. The treatment trees are more water- than light-limited. We hypothesise that the crown properties *cpa*, transparency and roughness are linked to each other when analysing the interaction effects of drought and competition. Therefore, trees suffering from drought stress and high competition reduced their already small crown dimensions to the lowest possible size at which they could efficiently survive. Roughness and transparency decrease as a follow-on effect of smaller and more compact crowns. This contrasts with the increasing roughness and transparency of trees under drought stress without competition. Due to this contrast, the crown properties roughness and transparency are not the ideal variables for detecting drought stress alone. In comparison, *cpa* reacted more strongly to drought, and should represent a good indicator for tree-vitality monitoring.

4.3. Conclusions for monitoring and research

In the past, crown attributes have proven difficult to measure. TLS is proved to be a powerful tool for measuring physical crown dimensions and to be more reliable than conventional field methods (Seidel et al. 2015). Trees do not have to be cut and manual time-consuming and costly surveys can be avoided. So far, the effects of drought stress have been based on visual observation from the ground or the laborious collection of broken branches and leaves (Rust and Roloff 2002). This study demonstrated that iterative TLS surveys may enhance the information gathered during measuring campaigns on common long-term experimental plots by obtaining a more thorough picture of growth patterns due to climate change or management plans. Crown size is an important factor which is closely related to light absorption and productivity (Binkley et al. 2013). Such accurate data of tree-crown dimensions are also essential for tree-growth modelling (Poschenrieder et al. 2016).

The presented tree vitality indicators obtained by TLS were not evaluated against a reference although they may include errors. Wang et al. (2019) reported for instance that TLS underestimated height of big trees, which may be due to occlusion of crown and stem parts. The occlusion problem might be mainly resolved choosing a sufficient of different scan positions. On the other side, TLS height measurements on Norway spruce trees in forests stands that covered a broad density range were found to be more accurate than common height measurements with the Vertex, a hand-held device based on the trigonometrical principle (Jacobs et al. 2020). Regarding crown dimensions, it may be more complex to find a suitable reference. Seidel et al. (2015) showed that crown attributes obtained from TLS were more closely related to preceding tree growth than those measured in the field. The question what should be used as a direct reference for abstract parameters such as crown transparency or roughness remains. What highlights the TLS measurements in comparison to the conventional measurement of *cpa*, transparency and roughness is the purely rational procedure without subjective influence. Still, tree-vitality monitoring could be developed towards more quantitative methods by application of TLS as traditional recording of crown transparency in the field has some disadvantages. Crown transparency is not directly measurable and must instead be carried out by well-trained field experts. Despite the photo comparison with reference images, there is a risk of systematic or random observer deviations, which require intensive training and standardisation exercises (Dobbertin et al. 2009). In addition, crown thinning is not cause-specific, i.e. different reasons cause similarly high crown transparency, for example insect damages. Further, it is also not clear whether the crown transparency of a tree is the result of a loss of vitality, or whether the tree is possibly recovering from stress. Reference values are therefore required to classify the characteristic. Roughness, on the other hand, represents a TLS developed indicator that could be considered in future

research. Tree vitality indicators should not be evaluated individually, as this can easily lead to misinterpretation (Dobbertin et al. 2009). The development of new indicators based on TLS enables to analyse several indicators and evaluate them together. In this study, we showed that TLS could be appropriate for measuring crown transparency and roughness of tree crowns. Taking into account not only one but also several tree vitality indicators, all of them going in the same direction, may confirm the influence of drought on tree properties (Dobbertin et al. 2009).

Furthermore, drought stress effects on trees could have an impact on the results of the modern and rapid estimation approach of estimating the diameter at breast height using the crown diameter computed by drone data (UAV). The significant smaller *cpa*, due to drought stress could lead to errors when estimating the crown-diameter-based $d_{1.3}$ measured from above using UAV. Thus, $d_{1.3}$ would be underestimated. This is made clear in Fig. 6, which shows the calculated allometry coefficient regarding *cpa* and $d_{1.3}$. It demonstrates how drastically the investment behaviour of the tree can change under drought stress. The control trees showed a positive allometry ($\beta > 1$), where *cpa* grows more than $d_{1.3}$. Vice versa, the treated trees, suffering under drought, had a negative allometry ($\beta < 0$). Here $d_{1.3}$ grows while the *cpa* shrinks. Crown shapes may change due to the impacts of climate change. Therefore, crown models within tree growth models must be questioned, as must the derived allometries. The higher frequency of extreme and extensive drought events (IPCC 2012) makes it even more important to consider drought stress effects in forest practice and ecological modelling. This is particularly true for the analysis of crowns, because of their spontaneous reaction to environmental and neighbouring changes.

5. Conclusion

TLS can offer new opportunities in identifying structural features in trees to measure and analyse indicators of tree vitality. Based on changes in tree shape parameters, TLS has the potential to be a rational and suitable tool for capturing indicators to evaluate the condition of a forest. We demonstrated that iterative TLS surveys might improve the measuring campaigns on common long-term experimental plots, in order to obtain a thorough picture of tree-vitality monitoring. The unique experiment “KROOF” combined with the TLS made it possible to get unique results about drought impacts on tree shape.

CRedit authorship contribution statement

Martin Jacobs: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Andreas Rais:** Supervision, Conceptualization, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Hans Pretzsch:** Supervision, Conceptualization, Methodology, Resources, Writing - original draft, 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.

Acknowledgements

We would like to thank Gerhard Schütze for all traditional measurements and the TLS data acquisition in the winter of 2012/2013.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A

Table A1

Overview of both scanners, RIEGL LMS-Z420i (RIEGL 2010) and RIEGL VZ-400i (RIEGL 2019), summarising the main characteristics.

Laser Measurement System (LMS)		RIEGL Z420i	RIEGL VZ-400i
Range ¹⁾	m	1000	800
Effective measurement rate ²⁾	meas./sec	11,000	500,000
Accuracy ^{3),4)}	mm	10	5
Precision ^{4),5)}	mm	4	3
Vertical field of view	°	80	100
Pulse mode		last-pulse	multiple target capability
Registration		artificial targets	automatic
Laser beam divergence	mrads ⁶⁾	0.25	0.35

1) Typical values for average conditions. Maximum range is specified for flat targets with size in excess of the laser beam diameter, perpendicular angle of incidence, and for atmospheric visibility of 23 km. In bright sunlight, the max. range is shorter than under overcast sky.

2) Rounded values.

3) Accuracy is the degree of conformity of a measured quantity to its actual (true) value.

4) One sigma at 100 m range under RIEGL test conditions.

5) Precision, also called reproducibility or repeatability, is the degree to which further measurements show.

6) Measured at the 1/e² points. 0.25/0.35 mrad corresponds to an increase of 25/35 mm of beam diameter.

A.1 Scan acquisition

Two different laser-scanning systems were used for the two surveys: RIEGL LMS-Z420i (RIEGL 2010) for winter 2012/2013 and RIEGL VZ-400i (RIEGL 2019) for winter 2018/2019. An overview of the two scanners, summarising the main characteristics, is provided in Table A1. For both dates, multiple scans were consecutively taken around the plots. In winter 2012/2013, two scans (horizontal and vertical) were performed for each scan position. The vertical and horizontal angular resolution was set to 0.05°, which in our practical experience, achieves a reasonable trade-off between scan-time and risk of disturbances due to tree movement through wind.

In the winter of 2018/2019, the resolution was chosen so that the scans were comparable to the TLS recordings in the winter of 2012/2013. Due to the angular measurement scheme of the scanners, which operate from the ground, the point density naturally decreases towards the top of the canopy. Furthermore, the laser beam is usually unable to penetrate tree compartments in order to perform measurements behind obstacles. These two effects result in rather sparse measurement densities in the upper crown and stem regions, especially if the crown parts near the scanner are dense (Hilker et al. 2010). Regarding the RIEGL LMS-Z420i, we attempted – with the RIEGL distance-measurement mode called “last-pulse” or “last-target” – to counteract these effects and record the deepest points within a footprint, thus gaining a higher proportion of returns from inner-crown regions compared to first-pulse mode. Utilising the pulsed time-of-flight method for laser range measurements, the RIEGL LMS VZ-400i enables the determination of the range to all targets a single laser pulse is interacting with (“multi-target capability”). Depending on the measurement program used, the maximum number of targets, which can be detected, varied (typically 4–15). In summary, the RIEGL LMS Z-420i in the last-target setting generates one deep point per laser beam, while the RIEGL LMS VZ-400i can generate 4–15 points per laser beam. Due to this difference of the two scanners, we did not focus on three-dimensional tree features. Instead, our crown target variables (*cpa*, transparency and roughness) were two-dimensional to take into account the ability of the newer

scanner to generate more points inside the crown space. This was done to exclude errors occurring in the three-dimensional analysis due to non-scanned areas of the upper crown region respectively. In winter 2012/13, artificial reference targets (reflectors) distributed in the scanned forest scenes enabled the co-registration of the scans. The data of all scan positions per plot were co-registered using the software RiSCAN PRO version 2.0.2 (<http://www.riegl.com/products/software-packages/ri-scan-pro/>). In winter 2018/19, the new automatic registration of the LMS VZ-400i was used so that artificial reference targets were no longer needed. Automatic registration and filtering were performed using the software RiSCAN PRO version 2.8.2. The entire point cloud was reduced using an octree to enable fast point-cloud processing without accuracy loss (Elseberg et al. 2013). This distributes the data evenly in space, whereby each cube with an edge length of 5 cm contains on average only one measuring point, which is set according to the centre of gravity of the original points in the cube. Both point clouds, from winter 2012/2013 and winter 2018/2019, were post-processed via the software Cloudcompare, using the fine registration feature to register both clouds in the same project coordinate system.

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