

Environmental Research Letters



LETTER

OPEN ACCESS

RECEIVED
5 March 2020

REVISED
1 April 2020

ACCEPTED FOR PUBLICATION
3 April 2020

PUBLISHED
23 June 2020

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Tree growth at the end of the 21st century - the extreme years 2018/19 as template for future growth conditions

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Keywords: drought, tree-growth, forests, dendrometer
Supplementary material for this article is available [online](#)

Abstract

Using measurements from high resolution monitoring of radial tree-growth we present new data of the growth reactions of four widespread broadleaved tree-species to the combined European drought years 2018 and 2019. We can show that, in contrast to field crops, trees could make better use of the winter soil moisture storage in 2018 which buffered them from severe drought stress and growth depressions in this year. Nevertheless, legacy effects of the 2018 drought accompanied by sustained low soil moisture conditions (missing recharge in winter) and again higher than average temperatures and low precipitation in spring/summer 2019 have resulted in severe growth reductions for all studied tree-species in this year. This highlights the pivotal role of soil water recharge in winter. Although short term resistance to hot summers can be high if sufficient winter precipitations buffers forest stands from drought damage, legacy effects will strongly impact tree growth in subsequent years if the drought persists. The two years 2018 and 2019 are extreme with regard to historical instrumental data but, according to regional climate models, resemble rather normal conditions of the climate in the second half of the 21st century. Therefore the observed strongly reduced growth rates can provide an outlook on future forest growth potential in northern Central Europe and beyond.

1. Introduction

The two climatically extreme years 2018 and 2019 provide an ideal scenario to study the effects of drought on growth performance of forests in central Europe under projected future climate. The summer 2018 was the hottest on record for many central and northern-European regions. Sustained high pressure conditions over most of the summer blocked the Atlantic lows leading to record temperatures, sunshine hours and very low precipitation amounts (Buras *et al* 2020, Heinrich *et al* 2019). Coming from a wetter than average winter, 2018 exemplifies the conditions predicted by regional climate models for 2100, with a shift in precipitation pattern from summer to winter, significant warming and more sunshine in summer (Jacob *et al* 2008, Kreienkamp *et al* 2010). Soil water recharge was insufficient in winter 2018/19 and spring/summer 2019 were much warmer and dryer than the long-term average. Drought severity in 2019 was among the highest since the start of

the instrumental records. These severe drought conditions for two consecutive years led to drastic reductions in crop yields, historic low-water of rivers and lakes, dieback events in forests or forest fires (Buras *et al* 2020, Heinrich *et al* 2019), and therefore provoked serious concerns about future performance of local forests and tree species (Eichhorn *et al* 2020).

In the last decades a large number of studies dealing with climate change related growth reactions and adaptations of forests using retrospective and forward modelling approaches have been published (e.g. Lindner *et al* 2010, Spathelf *et al* 2014, Bauwe *et al* 2015, Harvey *et al* 2019, Trotsiuk *et al* 2020). The overwhelming majority of these studies agrees that adverse conditions, like increased soil waterlogging in spring, and especially severe drought stress in summer will lead to growth depressions, range shifts of species, drought damages and potential dieback events in forest ecosystems (e.g. Breda *et al* 2006, Hackett-Pain *et al* 2016, Cavin and Jump 2017, Trotsiuk *et al* 2020). Currently observed positive growth

trends in European forests induced by nitrogen fertilization (Etzold *et al* 2020) will probably be outweighed by increasing drought stress, especially in southern and eastern Europe (Lindner *et al* 2010) and for beech (Zimmermann *et al* 2015). For example, a growth decline of more than 20% at the end of the 21st century was predicted for European beech and pedunculate oak for Northern Central Europe by Bauwe *et al* (2015). Similar dimensions of future drought induced growth decline are predicted by Trotsiuk (2020).

And indeed, first assessments of forest vitality in Germany in reaction to the 2018/19 drought sequence report severe damage in deciduous and coniferous forest stands as well as dieback events especially in spruce forests (Bayerisches Staatsministerium für Ernährung Landwirtschaft und Forsten 2019, Sächsisches Staatsministerium für Umwelt und Landwirtschaft 2019, Dammann *et al* 2019, Langer *et al* 2020). The consecutive record drought years 2018 and 2019 present a glimpse into the future and allow the investigation of direct, short term consequences of predicted future climate conditions on tree species and forest growth.

In this article we use high-resolution radial growth data from European beech (*Fagus sylvatica* L.), pedunculate oak (*Quercus robur* L.), sycamore (*Acer pseudoplatanus* L.) and hornbeam (*Carpinus betulus* L.) across a range of site conditions and management regimes in Northern Germany to explore the effects of two consecutive drought years on (1) absolute radial growth, (2) onset and cessation of growth. Based on our results we (3) provide an outlook on future growth performance of four central European forest tree species under projected regional climate scenarios.

2. Methods

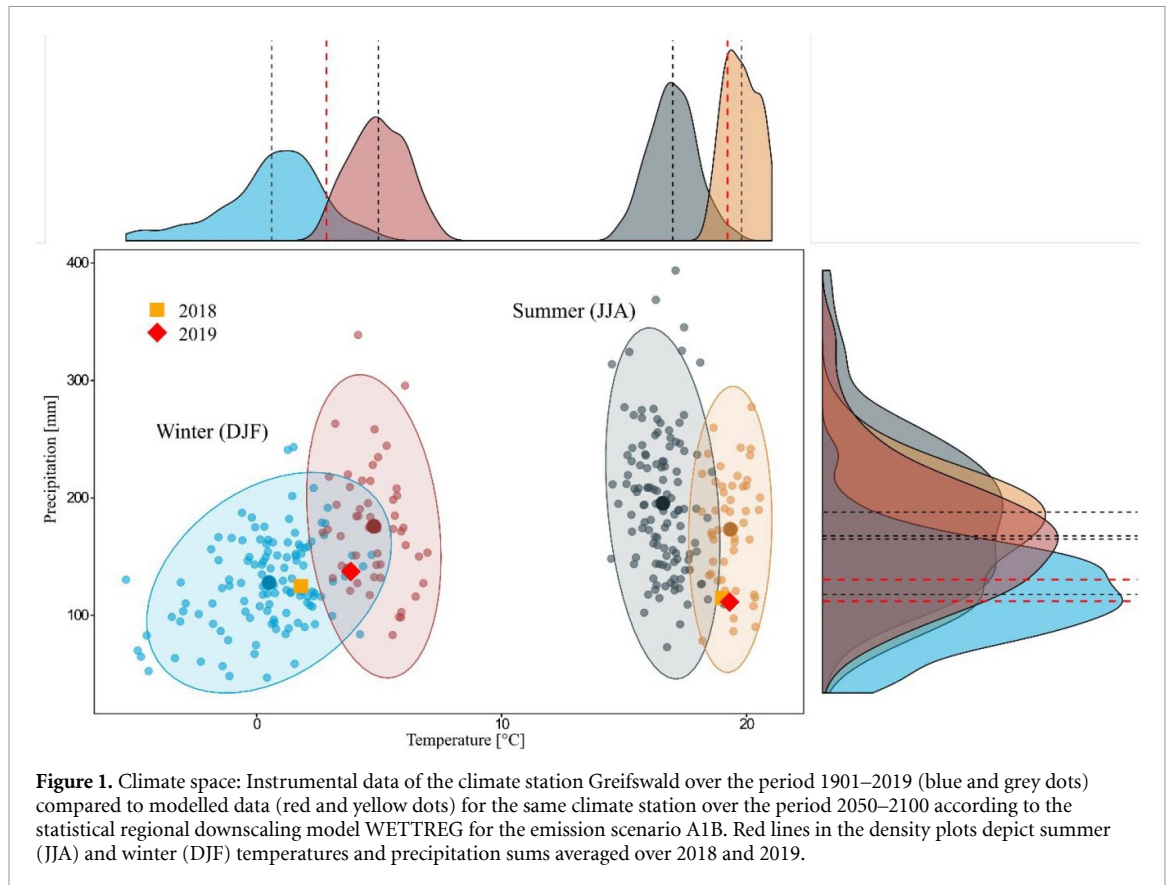
Data from three long-term-ecological-monitoring (LTER-D) plots situated in old-growth, mixed broadleaved forests in NE-Germany close to the city of Greifswald was used for this study. The experimental design follows a gradient of decreasing management intensity from 1) currently managed, via 2) unmanaged since 60 years, to 3) unmanaged since at least 200 years. Soils at all plots developed from glacial till parent material and are classified as stagnic luvisols (Buczko *et al* 2017) and Cambisols (Dieckmann *et al* 2015). They cover a range of substrates from sandy-loamy to pure sands and accordingly differ in their water holding capacity. Soil-fertility is similar with good nutrient supply and well developed humus layers at all sites (Dieckmann *et al* 2015, Buczko *et al* 2017). At each plot dominant beech and oak trees with an age of more than 150 years were chosen as target trees, complemented by the typical companion species hornbeam and sycamore which have ages around 100 years.

Radial stem size variations of the target trees are monitored with point dendrometers (Type DR, Eco-matik, Munich, Germany) installed at a height of 3 m on the north facing side of the stems to avoid distortions from direct solar radiation. For oak, part of the thick outer bark was removed to minimize noise in the signal due to bark shrinkage and swelling. Radial displacement of the sensor is measured with an accuracy of $\sim 1,5 \mu\text{m}$ in one-minute intervals. For our analysis we used data from a total of 40 trees: 15 beeches, 13 oaks, 5 hornbeams and 7 sycamores. The data was quality controlled and averaged over 30-minute intervals.

Micrometeorological data like air temperature, relative humidity and photosynthetic active radiation (PAR) are collected at each site and flanked by soil volumetric water content probes (Campbell Scientific CS655) in depths of 10, 20, 50 and 100 cm. Litter traps provide quantitative information about variations in annual seed production (masting), collected each year in late fall (November/December). Detailed information about site and tree characteristics as well as the length of the monitoring time series can be depicted from table S1.

Climate data used in this study was provided by the German weather service (DWD) for the climate station Greifswald ($54.0967^\circ\text{N}/13.4056^\circ\text{E}$). The data is openly available via the Climate Data Centre (CDC) at <https://cdc.dwd.de/portal/>. Time series of temperature and precipitation start in 1899. Data was checked for homogeneity and missing values were extrapolated from nearby climate stations. A climate space of temperature against precipitation was plotted using summer (June, July, August) and winter (December, January, February) temperature means and precipitation sums. To exemplify the predicted change in these parameters by the second half of the century, modelled data for the same climate station was added to the climate space from the statistical regional downscaling model WETTREG (Kreienkamp *et al* 2010, 2013) based on the emission scenario A1B. This data was provided by the German Climate Computing Center (DKRZ) at <https://cera-www.dkrz.de/WDCC/ui/ceraresearch/>. Density distributions of the historical and modelled future station data were additionally plotted and compared. Soil moisture development over 2018 and 2019 in our sites was plotted separately for sandy and loamy soils substrates. Exemplarily, data for 50 cm soil depth is presented here because of very similar temporal development pattern between all monitored depths. Soil moisture indices for the region were taken from the German Drought monitor (Zink *et al* 2016), considering the entire soil column ($\sim 1,8$ m depth).

Data processing for explorative data analysis of the dendrometer data included a range standardization, to remove individual variation as much as possible and allow for species-wide comparisons and broader generalizations of the raw dendrometer



series. We standardized the raw dendrometer series by dividing the raw values by an ‘expected’ tree-growth of each individual, estimated from average growth increments, i.e. asymptotes of the dendrometer curves, from the pre 2018 monitoring period (2013–2017; see figure S1 for deviations of temperature and precipitation over these years from the long-term average).

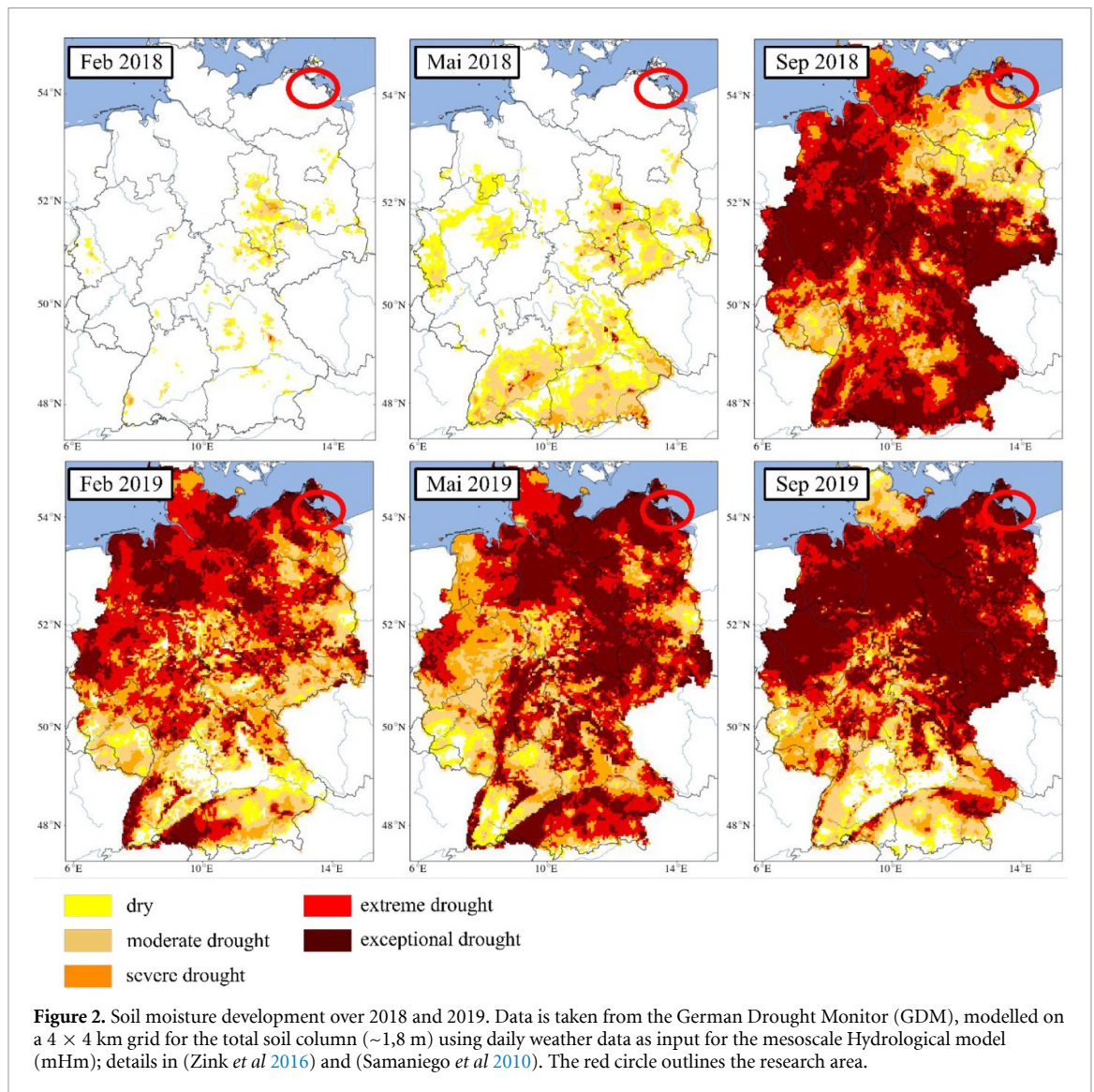
After removing individual tree signals we estimated expected growth patterns of each species by treating previous monitoring years (2013–2017) as a probability space, delimited by species-wide extreme values of the standardized dendrometer curves for each timestamp. In addition, species specific mean curves for the two single years 2018 and 2019 were computed to facilitate comparison. The curves were smoothed using generalized additive models to exclude short term fluctuations of shrinkage and swelling. Finally, onset and cessation of tree-growth was estimated for the two years based on the species specific mean curves. A sigmoidal growth curve was fitted to the year averages and the dates at which 5% and 95% of annual growth was completed were defined as onset and cessation of the growth period (Brewer *et al* 2011).

3. Results

Placing the summer and winter weather conditions of 2018 and 2019 in climate space of observed and

projected climate variability, clearly indicates that concerning summer situation both years are extreme with regard to the instrumental data, but resemble ‘normal’ conditions over the second half of the 21st century (figure 1). Winters of 2018 and 2019 have been warmer than the long term average but precipitation amounts were not significantly different from the long term winter sums. Model predictions indicate a shift towards increasing winter precipitation though.

Soil water content in our plots was high in spring of 2018 but dropped to low values by mid-July (figure S5). At the end of the vegetation season, in September 2018, severe soil drought of the total soil column was recorded by the German drought monitor for the region under study (figure 2). Insufficient soil water recharge in winter 2018/2019 resulted in lower soil moisture values at the start of the vegetation season in 2019 (figure 2). Interestingly, for the plot on sandy soils (figure S5, lower panel) this development was not expressed in the first meter of the soil column for which we have on-site data. Here soil moisture conditions were comparable between both years. Soil moisture reached low values in mid-July and approached zero in a depth of 50 cm at the sandy substrate from July 2019 on. For the plots on loamy substrate volumetric soil water content better resembled the broader trend depicted in figure 2 with lower soil moisture in spring 2019 compared to 2018. Notwithstanding these substrate specific differences in the



temporal trend of volumetric soil water content, trees showed comparable growth behaviour across all sites.

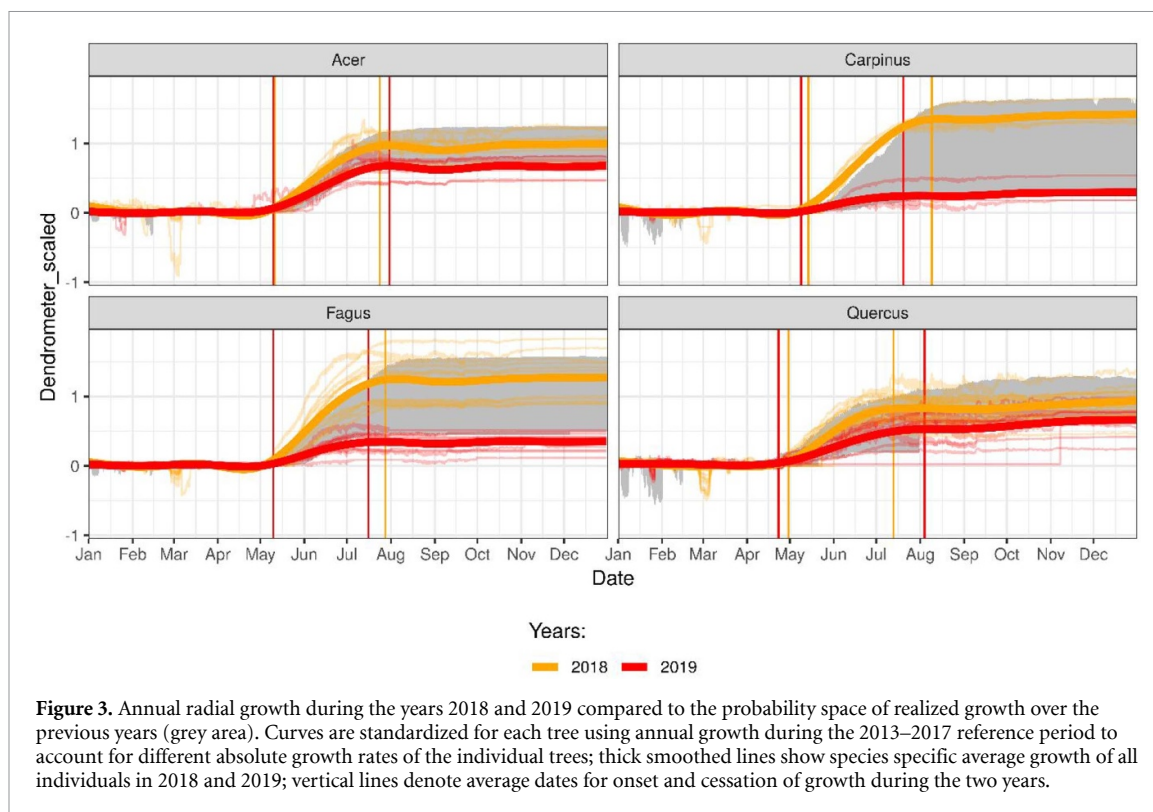
Facing severe meteorological drought over much of the vegetation season (figures S2–S4), radial tree growth in 2018 occurred at normal (oak, sycamore) or above average rates (beech and hornbeam, figure 3, table S2). In 2019 however, radial tree growth at all plots and across all species showed a strong growth reduction with values at or below the species specific probability growth space. In 2019, beech only realized 35.3% and hornbeam only 29.4% of the reference growth rates. However, both species showed strong fructification (masting) in 2019. Oak and sycamore on the other hand only showed moderate growth reductions in 2019, with oak still realizing 66.2% and sycamore 67.9% of their reference growth. Nevertheless, also for these species, growth in 2019 was outside or at the lower margin of the probability space of ‘normal’ growth over the previous years (figure 3). For hornbeam strong inter-annual variability of growth rates resulted in a very broad probability space. Management intensity did not show a clear influence on

growth responses of trees to the two extreme years (figure S6).

Onset of growth was similar in both years for all four species but growth cessation occurred approximately two weeks earlier in 2019 in hornbeam and one week earlier in beech. In contrast, oak and sycamore ceased their growth later in 2019 compared to 2018 (figure 3). In summary, although meteorological conditions over the vegetation seasons were comparable between the two years, radial growth was near or above average in 2018 but strongly reduced in all species in 2019, with the highest depression of more than 60% in beech and hornbeam.

4. Discussion

Monitoring of tree radial growth with dendrometers provides real time data for observing and reporting direct influences of extreme climatic events on forest growth. In case of the two extreme climatic years 2018 and 2019 we were able to derive growth reactions as deviations from average growth for four broadleaved



species in northern-Central Europe using ongoing long term monitoring time series from three mixed forest stands.

Significantly different growth reactions between 2018 and 2019 of all four studied tree species to otherwise climatically comparable growth conditions over much of the vegetation period highlight the pivotal role of soil water recharge and lag effects. Just recently it was demonstrated for beech and oak that most of the water transpired over the vegetation season has entered the soil as winter precipitation (Allen *et al* 2019). In that study both species almost exclusively showed a signal of winter precipitation in midsummer tree xylem water.

Profiting from sufficient soil water recharge during autumn 2017 and winter 2017/18 as well as warm temperatures already in the beginning of the vegetation period in 2018, all species in our study showed average or above average radial growth despite low summer precipitation and record high temperatures. Severe soil drought occurred not until most of the wood formation was completed (figure 2). However, soil moisture was potentially too low in August and September to sustain adequate photosynthesis rates for producing sufficient non-structural carbohydrates (NSC) as storage compounds. Incomplete soil water recharge in winter 2018/2019 combined with potentially low reserves of NSC resulted in very unfavourable growing conditions for tree-growth in spring 2019. This time depleted soil water reserves restricted trees from profiting from the warm temperatures and consequently their radial growth was strongly reduced. Drought induced

growth reductions in trees occur when soil water availability drops below a certain threshold to sustain sufficient plant water potentials. Trees react with stomatal closure to reduce water loss which results in lower photosynthesis- and xylogenesis rates (Ryan 2011, Choat *et al* 2018). If drought sustains, hydraulic failures due to xylem embolisms lead to loss of hydraulic conductivity and carbohydrate reserves get depleted (Mitchell *et al* 2013). Trees are limited in their capacity to regain functional water conductance again after drought and differences in ability to refill embolized vessels are one explanation for species specific recovery potentials (Yin and Bauerle 2017).

In addition, allocation of reserves to fructification affects radial growth, especially in beech. Beech is known as a masting species with strongly variable seed production between years (Vacchiano *et al* 2017). Triggered by the temperature difference of the two preceding summers, in 2019 a strong mast occurred which in combination with summer drought is known to result in a very narrow tree ring (Hackett-Pain *et al* 2017, Hackett-Pain *et al* 2018). Similar allocation pathways are likely at play for hornbeam, a tree-species known to also showing masting behaviour (Wesołowski *et al* 2015) with high fruit production in 2019.

4.1. Outlook on future growth

The assumption that summer climate conditions which are extreme today likely become average at the end of the 21st century is supported by model runs (Jacob *et al* 2008, Kreienkamp *et al* 2010). Under

the projected conditions of hotter and drier summer, strong impacts of increasing drought conditions on growth rates of all native tree-species and forests can be expected. Structural adjustments in crown-shoot ratio and total leaf area can be assumed under dryer conditions to reduce evaporative demand (Jump *et al* 2017, Laginha Pinto Correia *et al* 2019), which inevitably will result in lower growth, respectively forest yield. There is historic evidence for such scenarios during the medieval climate anomaly (MCA), a period of warm and dry conditions over much of Europe from ~1000–1300 AD. Several tree-ring datasets of oak and beech show significantly lower average growth rates during the MCA (Büntgen *et al* 2011, Büntgen and Tegel 2011, Cook *et al* 2015, Scharnweber *et al* 2019, Muigg *et al* 2020). Only parts of this discrepancy between contemporaneous and historic growth rates can be explained with the fertilizing effect of recent nitrogen depositions and higher CO₂ concentration in the atmosphere (Scharnweber *et al* 2019). It is more likely, that generally warmer and dryer summer climate during the MCA considerably diminished the productivity of historical forests. Current forest management often aims at concentrating growth to a limited number of final crop trees by means of thinning measures. These trees develop widely protruding crowns with high evaporative demands and are limited in ability to downscale their resource and water needs during droughts. This so called ‘structural overshoot’ (Jump *et al* 2017) might lead to higher drought sensitivity of large and older trees like the ones used in our study. Therefore our results, restricted to observations on dominant trees, might overestimate growth depressions of average stands. Higher drought sensitivities of large and dominant trees compared to smaller and suppressed individuals are reported frequently (Piutti and Cescatti 1997, Mérian and Lebourgeois 2011, Bennett *et al* 2015, Grote *et al* 2016, Trouillier *et al* 2019). Thus, for more accurate estimates of stand biomass development a complete sampling of all diameter- and social classes would be necessary (Babst *et al* 2014, Alexander *et al* 2018). Severe growth suppressions of dominant trees might partly be compensated by increasing growth rates of suppressed trees which are released from competition (Grote *et al* 2016). In addition, if drought also affects the tree density of a stand via mortality and rejuvenation, this has an influence on stand biomass and in turn alters individual tree biomass increment because of competition changes. Despite these biases and methodological challenges in upscaling of radial growth data derived from tree-rings or dendrometers, these proxies have been shown to provide rather robust estimates of stand-level aboveground biomass (Babst *et al* 2014, Dye *et al* 2016). In our study tree-dimensions of our monitoring trees are not significantly different between managed and unmanaged sites (table S1) which might be one reason for

similar drought responses of the treatments (figure S6).

From the comparison of growth during the last two years it becomes obvious that soil water recharge in winter is extremely important for future growth and survival of local forests. Climate models project a slight increase in winter precipitation for northern Central Europe (Jacob *et al* 2008, Kreienkamp *et al* 2010), which might partly compensate for the dryer summers. In contrast to field crops, trees and forests can tap deeper soil layers and therefore integrate their water use over longer time scales. The discrepancy between on-site measurements of our soil moisture probes covering the first meter and the modelled soil moisture development for the total soil column (figures 2 and S5) lends credibility to this assumption. Whereas our measurements show only slight differences between 2018 and 2019, especially at the sandy site, the modelled data (integrated over a deeper soil column), reveals much drier soil conditions in 2019. This is also mirrored in drought indices like the Standardized precipitation evapotranspiration Index (SPEI) which -if calculated over longer time-scales- integrates legacy- or lag effects (figure S3).

Severe growth reductions and dieback can be expected if multiple drought years occur one after each other. The cumulative effect will lead to amplified drought damages due to soil water depletion of deeper soil layers and carry over or legacy effects (Anderegg *et al* 2015, Wu *et al* 2018). The projected strong increase in frequency and intensity of extreme climate events like pervasive and hotter or ‘global change type’ droughts (Allen *et al* 2010, 2015, Carnicer *et al* 2011) will be more critical for forest vitality than a general warming trend (Trotsiuk *et al* 2020). Our results from the two consecutive drought years 2018 and 2019 seem to confirm this assumption: The above average growth in 2018 was most likely due to sufficient soil water supply, and trees profited from warmer summer temperatures. The strongly reduced growth in 2019 then seemed the result of a cumulative second drought year without sufficient soil water recharge in winter. Results from an extensive network of permanent monitoring plots confirm that during hot summers reduced plant water availability had a stronger effect on productivity in beech forests than temperature (Trotsiuk *et al* 2020). In that study net primary productivity was reduced by more than 25% in lower elevation beech forests during warm and dry extremes. We can therefore expect that summer drought will counteract the prevailing positive growth trend in European forests caused by sustained nitrogen depositions (Etzold *et al* 2020).

4.2. Species specific reactions

Based on available ecophysiological and observational evidence due to different traits and adaptations, drought tolerance of the four species under

study could be ranked in the order oak > hornbeam > sycamore > beech (Ellenberg 1996, Gebauer *et al* 2008, Köcher *et al* 2009).

It is therefore not surprising that oak shows comparably little growth depressions in 2019. It is widely accepted that oak is more drought tolerant than other temperate broadleaved species, and especially in mixture with beech shows increasing competitive ability with decreasing precipitation amounts (Scharnweber *et al* 2011, Cavin *et al* 2013, Mette *et al* 2013, Vitasse *et al* 2019, Vanhellefont *et al* 2019). Oak can maintain photosynthesis at low water potentials (Raftoyannis and Radoglou 2002) sustaining a constant but comparably low sapflow stream under drought stress. Different adaptations like deep rooting depth and ring-porous wood structure make oak less vulnerable to sustained droughts (Scherrer *et al* 2011).

Hornbeam on the other hand with its continental distribution is commonly also regarded as a drought tolerant species (Köcher *et al* 2009). Deviating from this, in our study hornbeam showed the strongest growth decline of all four species. This strong decline might result from a combination of mechanisms. It might partly reflect the very high fruit production of hornbeam in 2019 and the preferential allocation of carbon to reproduction. It might also be that under intense drought stress, allocation of carbon is shifted from stems into roots so that low radial growth in single years in hornbeam can be even interpreted as an adaptation measure. We also have to mention that hornbeam has a very eccentric growth and that we cannot exclude the possibility that the severe measured growth decline might be partially a result of different allocation in stem growth.

Similarly the rather moderate growth decline of sycamore was not to be expected, as this species is commonly ascribed as being very susceptible to drought (Gebauer *et al* 2008, Köcher *et al* 2009, Scherrer *et al* 2011). Compared to beech growth of sycamore is more influenced by early spring conditions (Battipaglia *et al* 2008), and it can sustain higher leaf water potentials even under low soil moisture conditions (Köcher *et al* 2009). Under drought stomata closure in sycamore occurs earlier than in beech and sapflow is manifestly reduced (Scherrer *et al* 2011). In our study the length of the growing season 2019 was not shortened for sycamore despite much dryer conditions compared to 2018. Compared to the other species in our sites sycamore trees are younger and smaller, which might play a role in their higher resilience to drought. In general, drought sensitivity of trees is increasing with size and/or age (Merlin *et al* 2015, Trouillier *et al* 2018).

Finally beech showed very pronounced drought stress symptoms in 2019. It is generally agreed that severe summer droughts markedly reduce radial growth in this species and that recovery can be very slow (Peterken and Mountford 1996, Cavin *et al* 2013). Especially the combination of summer

drought and high reproductive effort—a combination that occurred in 2019—results in formation of very narrow tree-rings (Hackett-Pain *et al* 2017). Summer drought has become increasingly important for beech growth over the last decades (Harvey *et al* 2020) and growth rates of beech are considered to decline considerably under further warming (Leuzinger *et al* 2005, Scharnweber *et al* 2011, Vanhellefont *et al* 2019, Trotsiuk *et al* 2020) especially in the core range of its distribution (Cavin and Jump 2017). The coming years will show how quickly a recovery of beech can take place and how strong expected legacy effects of the combined drought years 2018/19 will alter forest structure and growth. The intensity of legacy effects is found to be stronger after late-season (August/September) and multi-year droughts and for diffuse-porous trees (Kannenberg *et al* 2019) which in our case might provide competitive advantage for the ring-porous oak over the other diffuse porous species.

In summary, severe growth reductions can be expected for deciduous tree-species in northern Central Europe under the predicted dryer and warmer future growth conditions. Specifically, global change type droughts which are forecasted to occur more frequently in the near future will change the competitive ability of most tree-species and therefore not only affect absolute growth rates but also whole forest structures and species compositions.

Our results underline the value of real time monitoring of forest growth and how it can be used for observing and directly reporting influences of extreme climatic events on forest growth. Initiatives like the newly implemented DendroGlobal database (Fonti *et al* 2016) allow for spatially broader analyses of daily tree growth responses to weather conditions and weather extremes and provide the basis for a mechanistic understanding of species-specific reactions of tree-growth to a changing climate. Practitioners might use this information for updating adaptation measures in order to sustain functioning forest ecosystems in a warmer and dryer future.

Acknowledgments

The study is a contribution to the research consortium BaltRap (The Baltic Sea and its Southern Lowlands: Proxy-Environment interactions in times of rapid changes) funded by the Leibniz Association. The study sites are part of the German Long Term Ecological Research network (LTER-D) and the monitoring is supported by the Terrestrial Environmental Observatories (TERENO) of the Helmholtz Association. T S and R C G received funding from the German Federal Ministry of Food and Agriculture and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Waldklimafonds-project FOMOSY-KK. We acknowledge support for the Article Processing Charge from

the DFG (German Research Foundation, 393148499) and the Open Access Publication Fund of the University of Greifswald. We thank two anonymous reviewers for their valuable comments on an earlier version of the manuscript.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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