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**Research Paper** 

# Growth patterns and effects of urban micro-climate on two physiologically contrasting urban tree species



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## G R A P H I C A L A B S T R A C T



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# ABSTRACT

Urban tree plantings for climate-adapted and resilient cities need to consider growth, vitality and ecosystem services of the planted tree species particularly during drought. However, information on growth and ecosystem services of urban trees under changed climate conditions are rare for most species. This study investigated the intra-annual growth patterns of two common but physiologically contrasting urban tree species: small-leaved lime (*Tilia cordata*) and black locust (*Robinia pseudoacacia*). Although meteorological variables at the study site in the outer city center of Munich, Germany for the year 2016 were similar to the long-term average climate (1961–1990) different growth patterns were found. This was mainly influenced by species characteristics (water use efficiency, wood anatomy) leading to different transpiration rates and reaction patterns to drought stress. Moreover, species' drought reactions compared to past years were analyzed in detail with a retrospective dendrochronological approach. Distinct species patterns were identified, highlighting the greater drought tolerance and reacovery of *R. pseudoacacia* compared to *T. cordata*. These results show that under a drier and warmer climate *T. cordata* can provide more canopy air cooling for short periods of time due to high transpiration, albeit this is at the expense of great water demands and following growth declines under water shortage. Contrary, *R pseudoacacia* proved to be a more suitable and adapted species at sites with less water availability due to better

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water use efficiency, even at the cost of low canopy transpiration though higher soil moisture and latent heat exchange from the soil.

# 1. Introduction

In the past urban tree selection for plantings was mostly based on aesthetic demands while nowadays the ecosystem services of green infrastructure are getting more and more attention (Gómez-Baggethun & Barton, 2013; Sæbø, Benedikz, & Randrup, 2003). In many US cities, planting programs are being implemented to include the environmental and health benefits of urban trees in species selection (McPherson & Simpson, 2003; Pincetl, Gillespie, Pataki, Saatchi, & Saphores, 2012). The benefits which arise from appropriate tree selection can be various starting from air cooling and shading (Akbari, Pomerantz, & Taha, 2001; Rahman, Moser, Rötzer, & Pauleit, 2017), increased biodiversity (Dobbs, Escobedo, & Zipperer, 2011) and air quality (Brack, 2002), mitigation of rainwater-runoff (Xiao, McPherson, Ustin, Grismer, & Simpson, 2000), carbon sequestration (Nowak, Greenfield, Hoehn, & Lapoint, 2013), noise reduction (Escobedo, Kroeger, & Wagner, 2011) to a better health of pedestrians (de Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003).

Conversely, only few studies deliver more detailed information on relationships between quantity and quality of urban trees and their provided ecosystem services. Konarska et al. (2015) for example studied transpiration and cooling of seven mature urban tree species in Sweden and showed that Quercus robur and Prunus serrata provided the greatest cooling effects. Moser, Rötzer, Pauleit, and Pretzsch (2015) calculated the carbon storage, shading and cooling ability in different age classes for two urban tree species in Germany (Tilia cordata and Robinia pseudoacacia). However, under a drier and warmer climate, many species will show decreased health and growth due to heat and drought stress respectively, providing less services to mitigate climate change (Pretzsch, Rötzer, Pauleit, & Moser, 2015; Sjöman, Hirons, & Bassuk, 2015). Data of growth and service provision are still rare for the most common urban tree species of different age classes at various urban settings, making targeted urban tree selection even more challenging. As Rahman et al. (2017) found out for two common tree species, the cooling ability of urban trees depends not only on tree age and vitality but also on the water use efficiencies and proportion of paved surfaces of the planting site.

Most of the studies about the impacts of urban trees on the city climate, which analyzed the effects of different urban tree species did not consider the effects of the prevalent site conditions on tree growth and health. Impervious planting pits have various disadvantages for trees like less access to soil water and nutrients (Morgenroth & Buchan, 2009), limited space for rooting (Bühler, Kristoffersen, & Larsen, 2007; Grabosky & Bassuk, 1995), mostly compacted soils with less aeration (Morgenroth & Buchan, 2009; Rahman, Stringer, & Ennos, 2013). In contrast, grass lawns at parks provide a growing site more similar to forest sites with better growing conditions regarding water availability, rooting space and less compacted soil. Kjelgren and Clark (1992) studied the growth of Liquidambar styraciflua at three typical urban environments with strongly varying climatic conditions, at streets, parks and plazas. The results highlight how different micro-climatic conditions can influence the growth of urban trees with plazas providing harshest growing conditions due to high radiation and limited water availability. Consequently, trees planted at plazas had smallest crowns and vitality, affecting the provided ecosystem services. Climate change with less precipitation and warmer temperatures (Meehl et al., 2007) will further intensify drought stress of trees. While most tree species of temperate and Mediterranean regions perform well under current conditions, future climate scenarios will drive many species to the margin of their performance levels, causing growth and vitality

decreases due to less tolerance towards drought (Gill, Rahman, Handley, & Ennos, 2013).

Several studies (e.g. Roloff, Gillner, and Bonn (2008), Pretzsch et al. (2015) or Percival, Keary, and AL-Habsi (2006)) begun to analyze which urban tree species will still grow well under changed climates. Those species might be used for future plantings while other species which suffer of climate change should not be planted due to significant health decreases. Those assessments, though, are strongly dependent on the stand climate of the specific planting site and the overall climate of the city which can vary strongly over different geographical ranges. For instance, Rahman et al. (2017) found out that individual species characteristics and site conditions are the drivers of urban tree performance. For a better tree selection, Uehre and Herrmann (2017) proposed to distinguish between heat and drought tolerance of urban trees based on their species features (e.g. wood anatomy and water stress behavior). Therefore, some species can be heat tolerant due to increased transpiration rates and their bark and leaf traits, however are not drought tolerant since great amounts of water are necessary to sustain their high transpiration. This is in line with the findings of Moser, Rahman, Pretzsch, Pauleit, and Rötzer (2016), where T. cordata showed high growth and transpiration during a severe drought year, though this was limited to an open site with less compaction and high amounts of grass lawn. In contrast at a sealed, compacted site with small planting pits, growth decreases during the drought year and in years following to previous drought events were observed. Consequences of water stress are reduced health and damage preventing tree strategies like early leaf senescence further decreasing the aesthetic value and provision of ecosystem services, especially since greatest services (cooling, shading, air filtering and runoff reduction) are provided by large, mature trees with healthy foliage (Gómez-Muñoz, Porta-Gándara, & Fernández, 2010; Sjöman et al., 2015). Appropriate tree selection is even more essential to avoid unnecessary costs for replacement plantings due to less vitality or dead trees, increased costs for air conditioning and cleaning (Roy, Byrne, & Pickering, 2012; Soares et al., 2011).

To overcome the mentioned knowledge gaps, this study aimed to analyze the relationships of the climatic conditions of a typical urban site (streets with open, green planting pits) with the growth and service provision on two urban tree species in Europe under current and future climate conditions. The overarching goal of this study was to provide an in-depth understanding about the reaction patterns of two different species to changing climate conditions transferable to other planting sites. The gained knowledge will be helpful for future sustainable tree plantings in cities, ensuring healthy grown trees in temperate regions. To base recommendations for future plantings on empirical results, we chose two common but eco-physiologically contrasting (in terms of their growth characteristics and species features) urban tree species, Tilia cordata and Robinia pseudoacacia for our study. While T. cordata is shade-tolerant and grows with intermediate speed, R. pseudoacacia is light-demanding, fast growing and a nitrogen-fixing species (Keresztesi, 1988; Namvar & Spethmann, 1986; Roloff, 2013; Wurzburger & Miniat, 2014). Moreover. T. cordata is a native species of temperate regions, which will probably suffer under future climate conditions, R. pseudoacacia naturally origins in the humid eastern United States. This species proved to be very tolerant to drought and heat stress and occurs worldwide at drier and more stressful habitats (Roloff, 2013; Roloff et al., 2008). They have differing wood anatomies and contrasting strategies under water stress (T. cordata as diffuse-porous and anisohydric, R. pseudoacacia as ring-porous and isohydric). Due to their lifestrategies, T. cordata can sustain low water potentials during drought stress very well, though it transpires much water which can lead to

after-effects like reduced vitality and early leaf-loss. *R. pseudoacacia* on the other hand is characterized as a water-saving species, immediately reducing the stomatal conductivity during drought, albeit reducing photosynthesis as well (Klein, 2014; Sjöman et al., 2015; Taneda & Sperry, 2008).

Based on an approach with high-resolution growth data and derived increment core data, the following research questions will be answered:

- Do the intra-annual and inter-annual growth patterns of the two common urban tree species *T. cordata* and *R. pseudoacacia* differ?
- What influences do the meteorological conditions have on the growth patterns of these two species?
- How do the reaction patterns to drought differ between these species and how do distinct species-specific characteristics (wood anatomy, water use efficiency) influence the found patterns?

#### 2. Material & methods

#### 2.1. Site description

The study was located in the eastern part of the city of Munich, Germany. The climate of Munich is temperate, with a long-term (1961–1990) annual precipitation mean of 959 mm and a mean annual temperature of 9.4 °C (DWD, 2016). Munich has a pronounced urban heat island effect with increased temperatures of urban areas compared to rural areas, especially during nighttime with intensities up to 6 °C within the city center (Pongracz, Bartholy, & Dezsoe, 2010). The study site was situated at the former airport Munich-Riem, which was closed in 1992. Afterwards, the area was transformed in housing development, shopping malls and exhibition areas with large green areas including parks and public squares.

Two plots with ten trees each were selected in a linear distance of approximately 930 m (Fig. 1). Plot 1 contains *T. cordata* trees planted in

two rows at each site of a square with grass cover and a street in northern direction. The ten trees chosen for data collection were at the northern end of the plot in the middle of the tree row, starting from the eastern end. Plot 2 contains three rows with a large number of *R. pseudoacacia* trees in southern direction. The ten sample trees were five trees in each row close to a building site in the north. Between the two rows of the trees, a loose paved walkway covered with grass and gravel goes along. A paved street is next two the middle row in southern direction. Tree plantings at both sites were based on the same standards in terms of use of structural soils and volume of the planting pits of  $36 \text{ m}^3$  (Landeshauptstadt München Baureferat Gartenbau, 2016). The trees at both sites were not pruned and irrigated during time of measurement.

The two chosen tree species are both common urban tree species in Central Europe and major cities like Munich (Pauleit et al., 2002) with contrasting life strategies. The species-specific growth-transpiration relationship can be illustrated by the water use efficiency (WUE), which refers to the amount of plant material produced per unit of water used (Kramer, 1983; Raper, Steinbeck, Moss, & Whitehead, 1992). Therefore, we used the WUE as index for the performance of *T. cordata* and *R. pseudoacacia*.

Data collection was conducted from June to December 2016 and was based on four main steps:

- 1. Pre-acquisition of tree structural data (e.g. dbh, tree height, crown features)
- 2. Installation of permanent devices at the trees (dendrometer, sap flow) and acquisition of tree growth data and ecophysiology of 20 trees in total (minutely data from June-December 2016)
- 3. Installation of permanent weather stations and acquisition of meteorological data (minutely data from June-December 2016)
- 4. Increment core collection at the end of the permanent data acquisition for dendrochronological analyses of past interannual growth



Fig. 1. Sample plots in Munich, Riem with the T. cordata plot in the north and the R. pseudoacacia plot in the south. Source of basemap: Geoportal, Esri.

development (yearly data from 1988 to 2016).

#### 2.2. Tree structural data and site information

Prior to installation of permanent devices diameter at breast height (dbh), tree height, height to live crown base, crown diameter, crown projection area (CPA), open surface area of the tree pit (OSA), vitality and coordinates including elevation was recorded. Tree height was derived using a TruPulse 200 Laser Rangefinder. Crown radius and OSA of each tree were measured in eight intercardinal directions (N, NE, ..., NW) along the ground surface from the center of the trunk to the tip of the most remote downward-projecting shoot and to the last visible open, non-asphalted surface of the soil, respectively, according to Moser et al. (2015); Moser, Rötzer, Pauleit, and Pretzsch (2016). The leaf area index LAI was computed from hemispherical photographs taken during the fully leafed phase at the end of June by a Nikon Coolpix P5100 camera with fisheye lens and Mid-OMount following Moser et al. (2015). The resulting photos were processed with Win-SCANOPY (Régent Instruments Inc., Quebec, Canada) using the LAI-2000-G method based on Miller (1967) and Welles and Norman (1991).

# 2.3. Permanent devices for intraannual tree growth and ecophysiological measurements

The stem growth of the selected trees was measured continuously with stem radius growth precision dendrometers (Ecomatik, Dachau, Germany), which were attached at approximately 4 m tree height. The height for installation was chosen to avoid vandalism. The dendrometer measures the linear shifting of a small sensing rod fixed at the bark of the trunk. With stem contraction and expansion, the rod is displaced as well, translating the movement into an electrical signal (Drew & Downes, 2009; Liu, Häberle, & Loris, 1994; Mäkinen, Seo, Nöjd, Schmitt, & Jalkanen, 2008). Raw data were recorded every 5 min from June 2nd to December 31st 2016 and stored in CR800 data loggers (Campbell Scientific, U.K.) equipped with Campbell Logger Multiplexer (AM16/32B).

Further, to derive tree transpiration, sap flux density of all 20 trees was measured continuously from June 2nd to December 31st 2016 using thermal dissipation probes (Ecomatik, Dachau, Germany) after Granier (1987). With visually derived sapwood depth from increment cores, the total sap flow was calculated and converted to the daily transpiration rate following Rahman et al. (2017).

To assess the water use efficiency WUE of both species, daily increment radius growth (DD) was added to the trunk diameter at dendrometer height ( $Dbh_{DD}$ ) for each tree:

DbhDDdaily [cm] = DbhDD + 2 x 
$$\left(\frac{DD}{10}\right)$$
 (1)

With biomass equations of Čihák, Hlásny, Stolariková, Vejpustková, and Marušák (2014) for *T. cordata* and Clark and Schroeder (1986) for *R. pseudoacacia*, the daily biomass increment was calculated. Following Rötzer, Liao, Goergen, Schüler, and Pretzsch (2013) based on transpiration per tree and biomass increment per tree, the daily water use efficiency WUE could be derived for both species from June 2016 to November 2016:

$$WUE [g/l] = \frac{Biomass IncrementDaily}{TranspirationDaily}$$
(2)

#### 2.4. Permanent devices for meteorological data collection

Air temperature, precipitation, wind speed and photosynthetic active radiation PAR were measured with two Vaisala Weather Transmitters WXT520 (EcoTech Umwelt-Meßsysteme GmbH, Bonn, Germany) and a PQS1 PAR sensors (Kipp & Zonen, Delft, The Netherlands) at both plots. At the *R. pseudoacacia* plot, the station was installed on top of a street lamp post at 3.3 m height, which was 10 m away from the closest tree. The weather station was mounted on a 3.5 m cross-arm 2 m away from the lamp to minimize influence of trees and buildings. At the *T. cordata* plot, the weather station was positioned on top of a 3.5 m iron pole in 10 m distance to tree number 6 (Fig. 1). Data were recorded continuously in a 15-min resolution from June 2nd to December 31st 2016 on a enviLog remote data logger (EcoTech Umwelt-Meßsysteme GmbH, Bonn, Germany). Due to device failure in November and December 2016 the meteorological data of DWD (2016) for the city center of Munich was used for further data analysis.

Further, soil matric potential and temperature were measured using Tensiomark 1 (4244/1, range pF 0-pF 7) (EcoTech Umwelt-Meßsysteme GmbH, Bonn, Germany) installed vertically through the soil profile to a depth of 30 cm. At the *T. cordata* plot, the sensors were installed 4 m away from each tree trunk between the trees, while at *R. pseudoacacia* plot the sensors were installed between the rows of trees and between the trees of each row (Rahman et al., 2017).

#### 2.5. Statistical analysis of tree data, dendrometer data and climate data

All statistical analyses were performed with R (R Core Team, 2014). Two Sample t-tests were applied to check for statistical differences regarding the tree dimensions (dbh, tree height, etc.) between *T. cordata* and *R. pseudoacacia*. Data derived from dendrometer were cleared of error values (e.g. vandalism during the continuous data collection). Dendrometer displacement was converted in micrometer and daily diameter growth curves for each tree and finally for each species were calculated. To assess the influence of measured meteorological data on tree growth in 2016, daily radius increment was analyzed in respect to meteorological values via Spearman's rank correlation tests. Further, a Generalized Additive Mixed Model GAMM, R-package *mgvc* (Wood, 2011; Zuur, Leno, Walker, Saveliev, & Smith, 2009) with daily tree growth over time related to the species was developed:

$$DD_{dailyij} = f(doy_i, \mathbf{species}_i) + \mathbf{species}'_i * \boldsymbol{\beta} + \beta_0 + b_i + \varepsilon_i$$
(3)

The index *i* represent the random effect on tree level. The function f() is a non-linear smoothing function which describes the course of the radius growth over the days of a year. This function is allowed to be different for each species. The vector  $\beta$  corresponds to the fixed linear effects connected to the species, and  $\beta_0$  is the model's intercept. The random effects on tree level,  $b_i$  are assumed to be normally distributed with an expectation of zero, and the same assumption is made for the independent identically distributed errors  $\varepsilon_i$ .

#### 2.6. Past interannual tree growth - increment core collection

Of all studied trees at both plots increment cores were extracted at the end of the study period to study the past growth. Two cores in northern and eastern direction were collected at dbh level. Further processing of the cores included mounting on wooden boards, sanding and polishing using progressively finer sand papers. The sanding was applied to flatten the cores, whereas the polishing increases the visibility of the cross-sectional area (Speer, 2012). The annual tree-ring width was measured with a Lintab digital positioning table with a resolution of 1/100 mm (Rinn Tech, Germany). The program TSAP-Win was used for data acquisition and further cross-dating of the time-series (Rinn Tech, 2010). All following analyses were carried out with Rpackage dplR (Bunn, Korpela, Biondi, Campelo, Mérian, Qeadan, & Schulz, 2015). The derived tree-ring series were detrended with a double detrending process, applying modified negative exponential curves and cubic smoothing splines (20 years rigidity, 50% wavelength cutoff, further averaged with Tukey's biweight robust mean). The autocorrelation of every series was removed using autoregressive models (maximum order of 3). The resulting chronologies for both species were then used for further analyses of climate-growth relationships. The statistical validity of the chronologies was assessed by the Expressed

Population Signal (EPS). The EPS quantifies the degree to which the final chronology represents the hypothetically perfect chronology (Briffa & Jones, 1990). From the chronologies, the age of the analyzed trees was derived. If the exact age of the tree was not clear (missing tree pith etc.), the age was back-calculated based on the undetrended average growth rate of the last ten years and the dbh of the tree.

To analyze the effects of climate and drought years on the growth of the studied trees, correlation analyses (response functions) with climate data were applied and a monthly drought index (SPEI) was calculated, based on data obtained from the German Weather Service DWD (2016). The response functions were calculated with the R package bootRes (Zang & Biondi, 2013), which computes 95% quantile limits based on 1000 bootstrap resamples to detect significance levels. Time-series of monthly mean temperatures and precipitation sums from March to October were correlated with the tree-ring series in the period from 1989 to 2016 for T. cordata and from 1992 to 2016 for R. pseudoacacia. The applied drought index SPEI (Standardized Precipitation Evapotranspiration Index) after Vicente-Serrano, Beguería, and López-Moreno (2010) was calculated with the R package SPEI (Beguería & Vicente-Serrano, 2013) and is based on precipitation and potential evapotranspiration PET. Hereby PET is computed following the Penman-Monteith equation (Allen, Pereira, Raes, & Smith, 1998) taking into account the monthly mean daily minimum and maximum air temperature in °C instead of ambient vapor pressure, monthly mean wind speed in km/h and monthly mean sunshine hours. A yearly SPEI for 1986-2016 was generated through averaging the monthly index values of the growing season from April to September. Years with a SPEI smaller than -0.5 were classified as moderate drought years and years with an SPEI smaller than -1 were classified as years with severe drought (Lough & Fritts, 1987; Vicente-Serrano et al., 2010). Hence 7 drought years within the period from 1986 to 2016 (SPEI values in brackets) could be identified: 2015 (-0.75), 2014 (-0.80), 2004 (-0.66), 2003 (-1.78), 1998 (-0.82), 1997 (-0.76) and 1992 (-0.67).

The influence of drought years on tree growth was then assessed with three indices after Lloret, Keeling, and Sala (2011) calculated on the basis of the yearly basal area increment BAI. *Resistance* (Rt) is the tree performance during drought (Eq. (3)), *Recovery* (Rc) is the tree's ability to recover from drought stress (Eq. (4)) and *Resilience* (Rs) gives insight to the tree capacity to achieve prior drought performance levels (Eq. (5)) (Lloret et al., 2011).

Resistance 
$$Rt = \frac{Drought}{Pre-Drought}$$
 (4)

$$Recovery Rc = \frac{Post-Drought}{Drought}$$
(5)

Resilience Rs = 
$$\frac{\text{Post-Drought}}{\text{Pre-Drought}}$$
 (6)

Rs > 1 indicate a complete return to former growth similar to values prior to the drought event, while a Rs < 1 means a loss in growth and a low resilience. Similar counts for Rt, values higher than 1 indicate a complete resistance of the trees to drought. Rc > 1 highlight a complete recovery from the drought event, values < 1 illustrate a loss in growth.

The pre-drought and post-drought periods were calculated including three years before and past drought, respectively, following Pretzsch, Schütze, and Uhl (2013) and Zang, Hartl-Meier, Dittmar, Rothe, and Menzel (2014) with the exception of the drought period of 2014–2015 which was only followed by the year 2016. The results for this period can be considered as preliminary.

# 3. Results

## 3.1. Tree structural data

Despite trees at both sites were planted at approximately the same time, the age and tree structures of the analyzed *T. cordata* and *R. pseudoacacia* trees varied significantly (Table 1). The *R. pseudoacacia* trees were younger, though having greater tree structures than *T. cordata* trees.

#### 3.2. Intraannual growth patterns

Fig. 2(a) presents the daily stem radius growth DD<sub>daily</sub> of both species derived from dendrometer data. While there was a phase of rapid growth in late spring and early summer, which lasted longer for R. pseudoacacia, DD<sub>daily</sub> in late summer, autumn and winter was very small for both species. R. pseudoacacia even showed a period of decline in autumn, followed by a small increase in winter. The modelled increment development in Fig. 2(b) was similar for both species until the beginning of April (doy 220). Between 06. September (day 250) and 05. November (day 310) a drop in DD<sub>daily</sub> was observed for *R. pseudoacacia*, which was not found for T. cordata. The overlapping error bands indicate that the growth patterns of both species were not significantly different, which could also be found for the actual values of DD<sub>daily</sub> due to the high deviation in growth particularly for T cordata. Overall, the model highlights a better, albeit not significant stem radius expansion of R. pseudoacacia compared to T. cordata (Table 2). The total growth curve over the year 2016 was found to be significant different for both species. Note that given estimate values only provide the linear term of the GAMM equation.

The maximum DD<sub>daily</sub> values were correlated with the measured meteorological values for each month of the measurement period in 2016 (Table 3). Some variables like PAR and soil moisture showed in some months less influence (CC < 0.2, p > 0.1) on stem radius expansion for both species, albeit the trend showed a negative correlation with maximum DD<sub>daily</sub>. Higher correlations were found with precipitation, vapor pressure deficit and transpiration (CC > 0.5). While vapor pressure deficit and transpiration and wind speed were positively correlated with DD<sub>daily</sub>. Strongest correlations overall were found with precipitation, especially in summer months (CC > 0.6). Differences of species are small, albeit *R. pseudoacacia* showed stronger correlations with transpiration and precipitation in summer months.

The average yearly correlations of tree growth with meteorological data are displayed in Fig. 3. Most variables illustrated a significant relationship with DD, while precipitation showed the strongest positive correlation for both species, followed by soil temperature, transpiration, PAR and air temperature for *R. pseudoacacia* and air temperature,

Table 1

Mean tree age, dbh, height, crown structures (start, radius, crown projection areas (CPA), length, volume) and leaf area index (LAI) with the standard deviation of the analyzed 10 *T. cordata* and 10 *R. pseudoacacia* trees. Different letters following mean values indicate significant differences of tree structures at p < 0.05.

Species	n	Age [a]	Dbh [cm]	Tree Height [m]	Crown Start [m]	Crown Radius [m]	CPA [m <sup>2</sup> ]	Crown Length [m]	Crown Volume [m]	LAI $[m^2/m^2]$
T. cordata R. pseudoacacia	10 10	$36^{a}$ $\pm 0.4$ $32^{b}$ $\pm 1.2$	$23.7^{a}$ $\pm 1.0$ $27.4^{b}$ $\pm 2.7$	$10.6^{a}$ $\pm 0.6$ $12.0^{b}$ $\pm 1.1$	$3.4^{a}$ $\pm 0.1$ $3.3^{b}$ $\pm 0.2$	$3.3^{a}$ $\pm 0.2$ $4.0^{b}$ $\pm 0.5$	$34.8^{a}$ ± 3.3 51.7 <sup>b</sup> ± 12.0	$7.2^{a}$ $\pm 0.7$ $8.7^{b}$ $\pm 1.1$	$250.7^{a}$ $\pm$ 38.7 $460.1^{b}$ $\pm$ 150.8	$3.6^{a}$ $\pm 1.3$ $2.6^{b}$ $\pm 0.7$
		± 1.2	± 3./	$\pm 1.1$	± 0.2	$\pm 0.5$	± 12.0	$\pm 1.1$	± 159.8	± 0.7



Fig. 2. Actual daily mean growth (a) and modelled mean growth (b) of *T. cordata* (green) and *R. pseudoacacia* (red). Applied model: generalized mixed model (GAMM) on the daily radius stem data (response variable) of *T. cordata* and *R. pseudacacia* with the individual tree code as random effect and with smoothing functions on the fixed effects doy (day of the year) in interaction with species.

#### Table 2

Results of the generalized additive mixed model on the daily tree growth DDdaily of all analyzed trees (response variable) with the individual tree code as random effect and the fixed effects doy (day of the year) and species and their interaction with a smoothing function f() on doy. Code: DDdaily ~ s (doy, by = Species) + Species, random = list (TreeCode = ~1).

Parameter	Fixed effect	Estimate ± SE	t-/F-value	р
$\beta_0$ Species' <sub>i</sub> * $\beta$ $f(doy_i, species_i)$ $f(doy_i, species_i)$ Random effect $d_i$ $\varepsilon$	Intercept Species (T. cordata) R. pseudoacacia T. cordata	$\begin{array}{r} 2.43 \ \pm \ 0.28 \\ - \ 0.25 \ \pm \ 0.38 \\ 1.33 \ \pm \ 0.18^{*} \\ 1.60 \ \pm \ 0.16^{*} \\ 0.78 \\ 0.36 \end{array}$	8.76 - 0.65 7.27/1209 10.33/816	< 0.001 0.51 < 0.001 < 0.001 - -

\* *Note:* given estimate values only provide the linear term of the GAMM equation.

PAR, wind speed and soil temperature for *T. cordata*. Surprisingly, despite the mostly negative correlations of transpiration and vapor pressure deficit with growth in Table 3, the overall correlation with growth

was positive for both species.

Assessing the daily biomass increment and daily transpiration rate, distinct species patterns were found (Fig. 4). While *R. pseudoacacia* transpired less per produced biomass, *T. cordata* needed significantly more water for growth. Due to the stem shrinkage negative values were found as well. In total, an average WUE of 8.11 g/l for *R. pseudoacacia* and 1.30 g/l for *T. cordata* were computed, confirming a better water use efficiency of *R. pseudoacacia* compared to *T. cordata*.

#### 3.3. Interannual growth patterns

The dendrochronological approach yielded in growth curves for the years 1988 to 2016 for *T. cordata* and 1992 to 2016 for *R. pseudoacacia* (Fig. 5). *R. pseudoacacia* showed an overall higher radius growth rate of 4.9 mm per year compared to 3.8 mm for *T. cordata* (Fig. 5a). However, the age-detrended growth curve revealed a better growth of *T. cordata* during the past two years and especially in the drought years 2015 and 2003, while the growth in the drought year 2006 was reduced for both species (Fig. 5b). The basal area increment also shows a higher increase for *T. cordata* during the past years (Fig. 5c).

#### Table 3

Correlation coefficient of the maximum daily radius increment of T. cordata and R. pseudoacacia with the measured photosynthetic active radiation (PAR), wind speed (WS), air temperature (AT), vapor pressure deficit (VPD), precipitation (Prec), soil temperature (ST), soil moisture (SM) and transpiration (Trans) for the month June, July, August, September, October, November and December of 2016. Symbols indicating p-values:  $^{\circ} < 0.1$ ,  $^{*} < 0.05$ ,  $^{**} < 0.01$ .

	-							
	PAR [W/m <sup>2</sup> ]	WS [m/s]	AT [°C]	VPD [kPa]	Prec [mm]	ST [°C]	SM [MPa]	Trans [ml per tree]
Maximum daily growt	h of T. cordata							
June	-0.26	0.04	0.14	0.04	$0.42^{*}$	0.00	0.24	-0.08
July	0.02	0.02	0.05	-0.26	0.50**	0.40*	0.03	$-0.32^{\circ}$
August	-0.27	$0.42^{*}$	$-0.43^{*}$	$-0.50^{***}$	0.70***	0.04	$-0.32^{\circ}$	$-0.41^{*}$
September	$-0.51^{**}$	0.57**	$-0.58^{***}$	$-0.63^{***}$	0.76***	-0.20	0.03	$-0.69^{***}$
October	-0.13	-0.04	0.30	-0.35°	$0.52^{**}$	0.51**	-0.05	-0.15
November <sup>+</sup>		0.32°	0.11	-0.21	0.46*			0.10
December <sup>+</sup>		0.13	0.06	-0.02	0.36*			
Maximum daily growt	h of R. pseudoacacia							
June	$-0.44^{*}$	0.19	-0.16	$-0.43^{*}$	0.65***	0.16	0.20	$-0.56^{**}$
July	0.35°	0.10	0.01	$-0.58^{**}$	0.85***	0.64***	0.04	$-0.36^{*}$
August	-0.18	0.40*	-0.21	$-0.50^{**}$	0.68***	0.24	0.15	$-0.59^{***}$
September	0.13	0.41*	0.02	-0.17	0.77***	0.36°	0.06	$-0.48^{**}$
October	-0.18	0.08	0.00	$-0.56^{**}$	0.61***	0.16	-0.03	$-0.36^{*}$
November <sup>+</sup>		0.03	-0.26	-0.12	0.00			0.36°
December <sup>+</sup>		0.04	0.11	0.16	-0.00			

<sup>+</sup> In November and December, no meteorological values were obtained due to measurement failure. Given corre-lation values calculated with data of DWD (2016) for Munich city center.

1.0

0.5

0.0

-0.5

-1.0

Correlation Coefficient [CC]



Fig. 3. Average correlations of *T. cordata* and *R. pseudoacacia* of the maximum daily stem radius expansion with air temperature (AT), photosynthetic active radiation (PAR), precipitation (prec), soil moisture (SM), soil temperature (ST), transpiration (trans), vapor pressure deficit (VPD) and wind speed (WS). Symbols indicating p-values:  $^{\circ} < 0.1$ ,  $^{**} < 0.05$ ,  $^{**} < 0.01$ .

Fig. 4. Water use efficiency based on the daily biomass increment and daily transpiration rate of R. pseudoacacia and T. cordata from June to November 2016.

Based on the monthly radius increment values of both species and monthly precipitation and temperature values, a response function on the tree ring formation depending on climatic influences was computed (Fig. 6). For both species only precipitation has significant influence on tree ring growth, while for the monthly temperature values no significant interaction with growth was found. Overall, the influence of temperature on tree ring growth was more positive in spring and early summer and more negative in summer and autumn for T. cordata, whereas the monthly ring width formation of R. pseudoacacia was negatively correlated with higher temperatures. Regarding precipitation, T. cordata was significantly negatively influenced by high rainfall amounts in March. In total, again in spring and early summer, a negative relationship was observed, compared to more positive influences of precipitation on tree ring growth in summer and autumn. For R. pseudoacacia, the observed patterns were more complex and changing; a strong positive correlation was found for August precipitation, while the other months showed varying patterns.

Based on the derived chronologies, the growth of both species in three drought episodes was analyzed. The calculated indices after Lloret et al. (2011) revealed a similar mean resistance for both species, however a higher recovery and resilience of *R. pseudoacacia* compared to *T. cordata* (Table 4). In detail, in earlier drought years (1997–1998) *R. pseudoacacia* displayed highest resistance, recovery and resilience, while for *T. cordata* similar patterns with the exception of a better recovery of the drought period 2003–2004 was found. As Fig. 7 highlights, *R. pseudoacacia* achieved during all analyzed drought events higher post-drought values than *T. cordata*. This indicates a better recovery ability from drought for *R. pseudoacacia* than for *T. cordata*. Except during 2014–2015, *T. cordata* showed best growth during the drought periods, however a growth decline afterwards.

# 4. Discussion

# 4.1. Tree structural data

The analyzed species differed substantially regarding tree dimensions. While *R. pseudoacacia* is a fast growing pioneer species, *T. cordata* grows slower during early age followed by a constant growth at later stage (Keresztesi, 1988; Larsen & Kristoffersen, 2002). Our data confirmed these species characteristics, since the measured tree dimensions



Fig. 5. Tree ring chronologies for *T. cordata* (black) and *R. pseudoacacia* (red). (a) Increment growth of both species in mm. (b) Ring width index derived by double detrending. (c) Basal area increment BAI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of *T. cordata* and *R. pseudoacacia* were significantly different. *R. pseudoacacia* had greater tree dimensions, although *R. pseudoacacia* trees were on average younger than *T. cordata* trees and had a smaller dbh, tree height and crown dimensions such as diameter, crown projection area and volume. Only LAI was significantly greater for *T. cordata* compared to *R. pseudoacacia*. These tree dimensions for the current age are in line with other studies of *T. cordata*. E.g. Lukaszkiewicz, Kosmala, Chrapka, and Borowski (2005) found greater dbh though similar height, while the trees Larsen and Kristoffersen (2002) studied had slightly smaller structures. Further, both species analyzed in this study displayed greater tree dimensions than Moser et al. (2015) found for *T. cordata* and *R. pseudoacacia* of the same age class in Munich. This indicates good growing conditions (e.g. light, nutrient and water availability) for the trees at both sites.

# 4.2. Intra-annual growth patterns and relationships with meteorological data

The intra-annual growth patterns of T. cordata and R. pseudoacacia obtained from high resolution dendrometer data differed significantly over the year. T. cordata displayed a strong stem radius expansion DD in spring and early summer followed by a steady DD with no significant increase or decrease. Though the data can only show the growth patterns from June to December, missing large parts of winter and spring, the observed patterns follow the characteristic growth curve of deciduous trees in Europe showed by other authors such as Rötzer, Biber, Moser, Schäfer, and Pretzsch (2017) and Zweifel, Zimmermann, Zeugin, and Newbery (2006). The growth from June onwards represents the steep increase in growth from beginning of the growth period in spring until the stem diameter reaches a steady plateau in summer and autumn after most of the growth has been accomplished. The study by Rötzer et al. (2017) also used high resolution growth data to analyze the growth of isohydric spruce and anisohydric beech under different treatments. They found similar growth patterns with a strong increase in spring due to beginning of the growth period comparable to the growth of T. cordata and R. pseudoacacia in spring and early summer.

These patterns have been found for other tree species and sites as well (e.g. Améglio, Bodet, Lacointe, and Cochard (2002) for peach and walnut, Zweifel et al. (2006) for oak, pine and spruce), especially the strong growth increase in spring was observed due to the beginning of the growth period and bud break, marking the beginning of a new growth cycle of deciduous tree species. Zweifel et al. (2006) found that until full leaf-flush, up to 45% of the total tree growth of a year already has been achieved. In this study, R. pseudoacacia and T. cordata showed strong growth until mid of September and beginning of August respectively, then DD remained on a steady level. Highest growth values were also observed until full-foliated phase, however radius measurements at the time of bud break were not included in our study. In particular for R. pseudoacacia this strong stem radius expansion before full-foliated phase is remarkable, since this species produces foliage very late starting from end of May to the beginning of June, therefore growth was mostly achieved by stored nutrients and earlier metabolism products (Hunter & Lechowicz, 1992). The late leafing of R. pseudoacacia is a consequence of the ring-porous wood anatomy of this species since ring-porous species must initiate new xylem replacing cavitated vessels before emerging leaves can be supplied with water (Lechowicz, 1984; Panchen et al., 2014). Diffuse-porous species like T. cordata can leaf out earlier due to a smaller risk of frost damage to the vessels and therefore can have a growth advantage over ring-porous species early in the growing season (Lechowicz, 1984; Michelot, Simard, Rathgeber, Dufréne, & Damesin, 2012).

The observed stem radius decrease of *R. pseudoacacia* in late summer and autumn was probably caused by low precipitation values in the months of July, August, September and October (40 mm, 89 mm, 95 mm and 38 mm respectively), as indicated by the high positive correlation values of growth with precipitation and negative correlations of growth with VPD and soil moisture in October. Due to its species features, *R. pseudoacacia* as a ring-porous, isohydric species reacts on drought stress with immediate decrease in stomatal conductance to avoid xylem cavitation, leading to diminished photosynthesis and growth (Klein, 2014; Lechowicz, 1984; Sjöman et al., 2015). The negative correlations of growth with transpiration



Fig. 6. Correlation functions of the monthly climatic parameters (temperature, precipitation) and residual chronologies from March to September of (a) *T. cordata* and (b) *R. pseudoacacia.* Dark grey bars indicate Pearsons's correlation coefficients meeting the 95% significance level based on bootstrap resamples.

### Table 4

Resistance Rt, Recovery Rc and Resilience Rs after Lloret et al. (2011) for *R. pseudoacacia* and *T. cordata* averaged for the drought periods 2014–2015, 2003–2004 and 1997–1998 as well as the mean values during all drought periods for both species.

	R. pseud	oacacia		T. cordata		
	Rt	Rc	Rs	Rt	Rc	Rs
Overall 2014–2015 2003–2004 1997–1998	1.94 1.18 1.55 3.08	1.89 1.28 1.51 2.88	3.18 1.51 2.39 5.63	1.97 1.15 2.10 2.66	0.81 1.34 1.25 0.81	1.90 1.42 2.23 2.07

especially during these summer and autumn months highlight a strong feedback reaction of growth on drought stress, especially since the trees were not irrigated. Downes, Beadle, and Worledge (1999) mentioned in their study that precipitation is strongly correlated with tree growth, with low precipitation causing tree stem shrinkage. Similar patterns were also found for spruce and beech trees under drought treatment and during a drought year by Rötzer et al. (2017). Here especially the ring-porous, isohydric spruce reacted with stem radius decreases to drought, while beech showed steady stem radius level regardless of the limited water supply. The xylem system with large vessels of ringporous species allows more rapid water transport, albeit induce a higher risk of cavitation under low water conditions or freezing in winter (Lechowicz, 1984; Zimmerman & Brown, 1971). Therefore, especially isohydric ring-porous species have a higher regulation capacity of their leaf water potential by regulating stomatal aperture. By reducing transpiration, the risk of cavitation is lower though reduced photosynthesis also reduces carbon assimilation, i.e. carbon starvation. Diffuse-porous, often anisohydric species such as T. cordata on the other hand, can sustain lower water potentials due to the smaller vessel size, maintaining stomatal conductance and therefore CO<sub>2</sub> uptake and growth. However, during heat and drought stress this strategy can lead to great risks of cavitation and in consequence hydraulic failure at the other hand (Gonzalez-Rodriguez, Cournède, & de Langre, 2016; Klein, 2014; Lechowicz, 1984; McDowell et al., 2008; Sade, Gebremedhin, & Moshelion, 2012). Moreover, anisohydric behavior leads to high rates of transpiration and water loss through stomata, possibly leading to stem shrinkage at sites with low water availability (Moser, Rahman, et al., 2016). Sade et al. (2012) discussed the advantages and disadvantages of ansio- and isohydric behavior, concluding that anisohydric strategies are especially beneficial with good water supply up to moderate water stress, but isohydric species will perform better under drought stress due to their better water use efficiency. Similar patterns were observed in this study, were the isohydric R. pseudoacacia produced more biomass with less water use than anisohvdric T. cordata. Better conditions in terms of soil water supply then can again lead to a better water uptake, better water status of cells and hence stem swelling



Fig. 7. Ring width index pre-drought, drought and post drought periods for (a) R. pseudoacacia and (b) T. cordata.

in particular after leaves absciss (Kramer & Kozlowski, 1960). This was observed for *R. pseudoacacia* in November, when stem diameter increased again. The observed stem radius increase can probably occur because of stored carbon and nutrients (in November trees are in a defoliated phase), however stem swelling caused by better water status is more reasonable. Brække and Kozlowski (1975) found similar patterns of stem growth in spring and summer, followed by a stem shrinkage for the isohydric *Pinus resinosa* due to cambial growth decrease. Stem expansion was explained with better water uptake and cell water saturation.

The relationships of stem radius with transpiration can also be found for PAR, vapor pressure deficit and wind speed, which also affected stem radius significantly (Kirschbaum, 2004; Rahman, Armson, & Ennos, 2014). Especially in summer, higher air and soil temperatures, higher PAR, greater vapor pressure deficit and less wind speed can negatively influence tree transpiration, causing higher rates of water loss and growth decline. The higher WUE of R. pseudoacacia also indicates a better efficiency of R. pseudoacacia in terms of growth and water use. When comparing the results of this study with the results of a similar study of Moser, Rahman et al. (2016) and Rahman et al. (2017) for T. cordata at two different sites in the city center of Munich during the severe drought year 2015, similar results regarding the summer months were found. In the drought year 2015 strong negative relationships of T. cordata's growth with measured climate variables (air temperature, soil temperature and moisture, transpiration and vapor pressure deficit) were found. Similar relationships of stem radius with PAR, transpiration, air temperature and vapor pressure deficit were observed for T. cordata and R. pseudoacacia in the summer months of 2016. However in contrast to 2015, the overall correlations of meteorological variables and transpiration with stem radius increase in 2016 were mostly positive. Due to the colder and wetter spring and early summer weather conditions, air and soil temperature, vapor pressure deficit and soil moisture acted as positive drivers of tree growth. In summer, with drier and warmer weather conditions, these patterns reversed compared to the found relationships in the summer months. Of course, site conditions (pit size, distance to buildings, influences by traffic, etc.) can vary tremendously over a city and also have major impacts on growth of urban trees. Apart from logistical (cost, vandalism, permit) constrains measuring the effects of speciesspecific growth patterns on identical growth conditions within a city area using experimental studies are hard to conduct. With our study, we can only provide insights in the growth mechanisms and climategrowth relationships of two common urban tree species (with 20 individuals) for the analyzed site and growth environment, which can be different at other growing sites of a city. However, especially the results for T. cordata at the greener, more open site of Moser, Rahman et al. (2016) are very similar to our observed results, highlighting the great influence of climate on tree growth, though this comparison is only

valid for *T. cordata*. In sum, a positive water status and stem expansion occurred, therefore transpiration and precipitation were positive drivers of tree growth. With the exception of precipitation and wind speed higher correlations with maximum stem expansion were found for *T. cordata* compared to *R. pseudoacacia*. Highest correlations of stem radius increase was found with precipitation, while other values such as air and soil temperature, soil moisture and wind speed showed only minor influence on stem radius increase.

## 4.3. Interannual growth patterns of T. cordata and R. pseudoacacia

Based on intra-annual growth patterns the annual stem increment growth rate of the R. pseudoacacia trees was higher compared to the T. cordata trees. Albeit, the basal area increment reveal that T. cordata has a higher growth on the long-run, possibly due to the higher age. The detrended RWI values highlight a more erratic growth of R. pseudoacacia during the past years and a more uniform growth of T. cordata. The results of the response functions on the temperature and precipitation correlations with tree ring growth over all growth years confirm the results on the intra-annual growth patterns of both species. While T. cordata reacts positively on higher temperatures and surprisingly on high amounts of water in spring and early summer, in late summer and autumn, high temperatures and high amounts of precipitation positively affect tree ring growth. The negative influence of precipitation in spring seems surprising, however T. cordata can react sensitive to water logging (Falk, Klemmt, Binder, & Reger, 2016) though the correlation coefficients are small. Moreover, cold temperatures in spring might also suppress growth and cause this negative feedback reaction. R. pseudoacacia on the other hand displayed hardly any recognizable patterns concerning the temperature-growth correlation with only hinting that high temperatures, in particular in summer, negatively affect tree ring formation. Precipitation amounts affect tree ring growth positively in summer. Overall, T. cordata displayed smaller correlation coefficients than R. pseudoacacia, highlighting that the growth of *R. pseudoacacia* is more sensitive to climate influences due to the species specific characteristics.

The calculation of the resistance, recovery and resilience indices based on Lloret et al. (2011) showed that both the species have an overall high resilience with *R. pseudoacacia* displaying even greater resilience than *T. cordata*. Therefore both species are able to reach similar growth levels after a drought period than before the drought (Lloret et al., 2011; Sousa, 1980; Tilman & Downing, 1994). In particular during young age, *R. pseudoacacia* showed extraordinarily good resilience of > 5. This is in line with the results of Lloret et al. (2011) and Ding, Pretzsch, Schütze, and Rötzer (2017) that younger trees generally exhibit greater resilience than older trees. However, the drought year of 2003 had the highest severity of all drought years, which could also have caused a decreased growth during this drought

#### period.

The recovery ability of R. pseudoacacia was better for all drought periods compared to T. cordata, highlighting a better recovery of R. pseudoacacia from drought events. The recovery index of T. cordata was on average smaller than 1, showing a decline in growth after the drought episode and a lower recovery ability. In terms of resistance, both species had similar values of around 2, indicating a surprising good growth of both species during drought events. Overall, the found species differences are in accordance with other findings on drought tolerance, see for example Pretzsch et al. (2013). They also found distinct species patterns with Norway spruce showing better resilience and resistance than European Beech and Sessile Oak. A further illustration of growth prior to drought events, during drought and past drought revealed similar patterns described by Lloret et al. (2011) and Pretzsch et al. (2013): R. pseudoacacia displayed for the drought periods 2003-2004 and 2014-2015 a decrease in growth during drought followed by good recovery for 2014-2015 and a growth smaller than prior to the drought period in 2003-2004. However, due to missing data after the year 2016 for the past-growth period following the drought year 2015, those results should be considered carefully and preliminary. In 1997-1998, the highest growth was observed during the drought period, possibly due to the young age of the trees and the comparably moderate drought years. R. pseudoacacia as isohydric species clearly showed a decrease in growth during drought and a good recovery which is in line with its species characteristics. T. cordata, on the other hand, displayed only in 2014–2015 the typical growth pattern normally found during drought years (Lloret et al., 2011). The patterns found for the droughts in 1997-1998 and 2003-2004 can also be explained with the anisohydric water conservation strategy of T. cordata. This species maintains a high stomatal conductance even during water limitation phases, ensuring continued growth. However, this pattern might lead to consequences as early leaf loss due to water stress and smaller growth in the following years.

# 5. Conclusion

The present study about the growth patterns of two common and physiologically contrasting tree species in terms of growth patterns and drought resistance highlighted how the growth of T. cordata and R. pseudoacacia was influenced by the surrounding site conditions. As expected by its ring-porous wood anatomy and isohydric water conservation strategy, the growth of R. pseudoacacia is strongly influenced by the water supply and transpiration, characterized through a better water use efficiency compared to T. cordata (WUE of 8.1 to 1.3 for T. cordata). Due to the diffuse-porous, anisohydric water stress strategy, growth of T. cordata trees is less reduced during droughts. However this strategy might lead to low-growth episodes after a drought, as the low recovery index of T. cordata illustrated. For future plantings, high water-using species can be recommended for sites with high plant available soil water contents. Under these conditions these species can buffer drought events and sustain high rates of transpiration and hence cooling. More water-saving species on the contrary, can be classified as both heat- and drought-tolerant, making them suitable tree species which should be considered more for future plantings regarding growth, ecosystem services and climate-adaptation to preserve green cities with vital tree species providing highest amount of ecosystem services. Especially R. pseudoacacia can regenerate quickly and its water-saving behavior sustains high soil moistures and therefore cooling by latent heat exchange from the soil. More measurements-including sites with differing growth conditions-on the growth patterns as well as on the cooling effect of both species are necessary, however, to confirm the found results, in particular for drought periods. While R. pseudoacacia provides better cooling through stored water and latent heat exchange, the sparse canopy might provide less surface cooling by shading than dense-foliated T. cordata, which should also be taken into consideration.

Moreover, the start of the growing season was not covered by our study, this part of the year could also provide important insights in the growth strategies of trees, in particular for two physiologically contrasting species like *T. cordata* and *R. pseudoacacia*. Future planting strategies should be based on confirmed knowledge on urban tree growth and performance under climate change conditions.

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