

Article

# Development of Fine Root Biomass of Two Contrasting Urban Tree Cultivars in Response to Drought Stress

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**Abstract:** Global climate change associated with rapid urbanization is projected to cause a worsening of environmental problems such as extreme heat and drought in cities. Urban trees play an essential role in improving air quality, fixing carbon, mitigating environmental degradation, and providing other ecosystem services. However, limited research has been conducted on belowground processes, which hampers a comprehensive understanding of the effect of climate change and urbanization on urban tree growth. Fine roots (<2-mm diameter) are the primary pathway for water and nutrient uptake by plants, and they considerably contribute to the survival of urban trees under drought stress. In this study, we conducted a controlled experiment on the development of fine roots of *Tilia cordata* Mill ‘Greenspire’ and *Tilia tomentosa* Moench ‘Brabant’ in response to drought stress via soil coring. Our results indicate that the two cultivars have different strategies for coping with drought. *Tilia tomentosa* ‘Brabant’, originating from drier regions, gave allocation to deeper soil parts priority probably to obtain more water. On the other hand, *Tilia cordata* ‘Greenspire’, which is native in Central Europe, showed a negative response to water shortage and preferred a more horizontal development of fine roots rather than a vertical development. Long-term studies are needed to gain a better understanding of the belowground processes of urban trees to select tree species and cultivars which are appropriate for planting in major cities, particularly with regard to future climate change.

**Keywords:** drought stress; fine root biomass; horizontal and vertical root growth; urban trees

## 1. Introduction

Global change including land-use change, elevated CO<sub>2</sub> concentrations, increased temperature, and increased rainfall variability is projected to have increasing impacts on the terrestrial ecosystem [1,2]. Simultaneously, urban areas around the world are expanding rapidly and will have more than 60% of the estimated world population by the year 2030 [3,4]. In this light, extreme heat is more extensive [5,6] and drought events can be exacerbated in urban areas due to many reasons, such as replacement of vegetation, storage of more sensible heat, and anthropogenic heat emissions [7–9]. Higher temperatures along with shifts in the precipitation rates may severely affect the urban environment of Central European cities [10]. It is therefore essential for cities to find effective solutions to mitigate the negative effects of climate change and accelerating urbanization [11].

Urban greening and trees can mitigate environmental degradation and provide ecosystem services accompanying global change and rapid urbanization [12]. As rapid urbanization is destroying natural ecosystems and degrading the environmental quality of towns and cities [13], trees can play a key role in improving urban air quality, reducing noise, attenuating storm-water flooding, and conserving energy, which have drawn increasing interest from researchers [14–18]. For example, Pretzsch et al. found that the urban climate can both accelerate and slow down tree growth, depending on the climatic zone of the given city [10]. In addition, Nowak et al. [19] studied how urban trees can filter pollutants that have adverse effects on human health. Furthermore, how urban trees cope with drought has attracted more and more attention. Roetzer et al. [20] showed that water deficit reduces photosynthetic productivity and tree growth. Moser et al. [21] found marked growth reductions occurred after serious drought events for some urban tree species.

Roots, especially fine roots, are the primary pathway for water and nutrient uptake. Although fine roots constitute only about 2–3% of the total biomass, they are also a prominent, possibly the most prominent, sink for carbon acquired in terrestrial net primary productivity [22–24]. It is therefore essential to obtain quantitative information of root development of urban trees as plants spend a considerable part of their energy on the production and maintenance of roots [25]. Multiple studies were developed for the growth of roots in cities, e.g., resource limitation feedback between root and shoot growth [26,27], factors impacting on root growth [28–30], root response to physical constraints [31,32] and to soil chemistry and contaminants [33]. Some researchers reported that fine roots could be invested more to enhance water uptake due to water shortage [34]. Stratópoulos et al. stated that valuable information about root biomass and root: shoot ratio could be important selection criteria for species and cultivars choice [35]. Hence, to acquire more knowledge of the development of fine roots of urban trees will contribute to a better understanding of improving their ecosystem services in cities.

Although urban trees have received increasing attention for their ecosystem services [36–39] and much attention has been paid to drought response of aboveground organs such as stems, twigs, and leaves, little is known about the response of the root system to water shortage [27,40,41]. It is crucial to obtain quantitative information of belowground processes especially in cities as the growth conditions of urban trees are even more challenging to those in natural environments [10,42]. In this paper, we designed a controlled experiment for two contrasting cultivars which are widely planted in Europe to analyze the fine root biomass in response to drought stress, as it was reported that global warming would most likely increase the frequency and duration of summer droughts in Central Europe [43,44]. The objectives of this paper were to (1) explore the development of the fine root biomass of two cultivars during the growing season; (2) investigate the development of fine roots in both the vertical and horizontal directions; and (3) discuss the carbon allocation of the two cultivars under drought.

## 2. Materials and Methods

### 2.1. Site Description and Cultivar Selection

The municipal nursery Munich-Laim (48°08′05″ N, 11°28′47″ E, 534 m a.s.l.) has an area of 42 ha and is located in the Munich Gravel Plain in southern Germany. The study site provides homogenous microclimatic and edaphic conditions. The annual mean temperature is 9.1 °C and the annual mean precipitation is 959 mm (DWD, 2017). In this study, we selected two cultivars *Tilia cordata* ‘Greenspire’ Mill and *Tilia tomentosa* ‘Brabant’ for research because *T. cordata* ‘Greenspire’ is a local cultivar planted widely in Central European cities while *T. tomentosa* ‘Brabant’ originates from drier regions of south-east Europe, which was ideal for making a comparison. The cultivar *T. cordata* ‘Greenspire’ was grafted on the same species and *T. tomentosa* ‘Brabant’ was grafted on the root system of *Tilia platyphyllos* Scop. This species is often planted in central and south Europe and widely used for grafting, especially hybridized with *T. cordata* as they had similar properties. To avoid the effect of transplanting shocks [45], trees transplanted in spring 2014 were chosen as their root system should have adequate growth.

## 2.2. Climate and Soil Moisture Measurements, Soil Samples

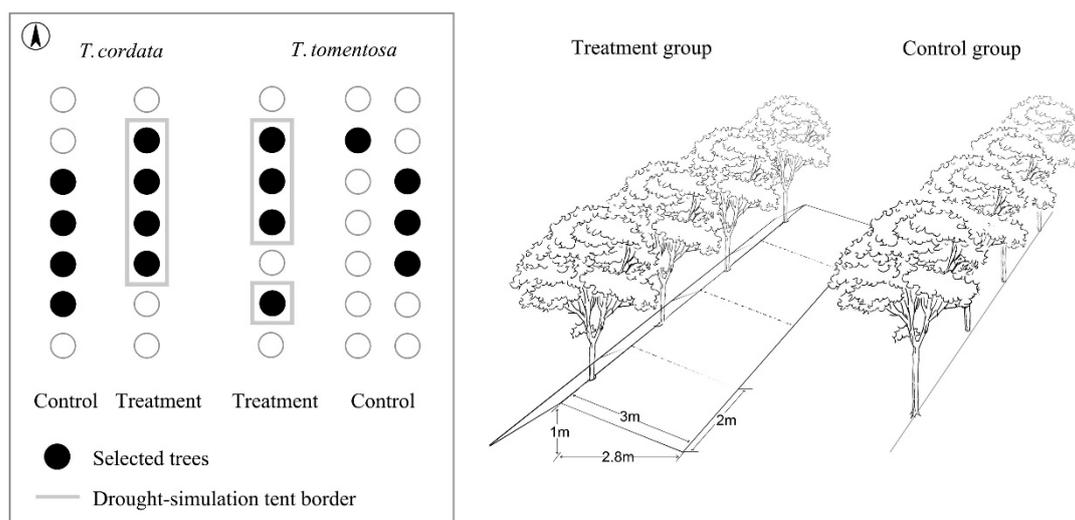
The data of air temperature, relative humidity, and precipitation were recorded with a weather station (Davis Vantage Pro2; Davis Instruments, Hayward, CA, USA) which was placed 450–600 m away from the research plots; and sampled every 10 min. In addition, precipitation data were obtained from the nearest weather station at Munich Airport from the German Weather Service (DWD) to calibrate some abnormal values. Vapor pressure deficit (hPa; VPD) was calculated from 10-min time interval air temperature as well as humidity data.

Soil samples were taken with a soil core in several locations around the trees. Afterwards, they were transported to laboratory for further analysis. First stones were removed from the soil samples. Then the samples were dried at 60 °C for 2 weeks to get the dry weight. At last large particles were filtered. The rest was transferred to prefabricated analysis program and evaluated. A portable soil moisture meter (UMP-1, UGT, Muencheberg, Germany) for point measurements in the upper 10 cm of the soil was applied throughout the whole summer. The readings were made at defined distances from all study trees. The soil moisture data was interpolated spatially for the two selected cultivars.

## 2.3. Drought Experiment in 2017

The individuals of *T. cordata* and *T. tomentosa* were planted in separate sites at 2 × 3 m spacing so that all the individuals had enough distance to each other to avoid mutual effect. The selected trees all had stem circumferences between 16 and 18 cm to obtain a similar initial status. In this way, eight random individuals of *T. cordata* (Tc) and *T. tomentosa* (Tt) were selected, respectively.

The trees were divided into two groups, one of which was set as the control group (c) and the other one as the drought treatment (t) group. As a result, four trees form a group: *Tilia cordata*-control (Tc-c), *Tilia cordata*-treatment (Tc-t), *Tilia tomentosa*-control (Tt-c), and *Tilia tomentosa*-treatment (Tt-t). For the control group, all the individual trees were exposed to ambient climatic conditions. For the drought treatment group, rainfall was excluded via rainout exclusion from May to November 2017. Therefore, several waterproof, translucent tarpaulins were connected to build a tent with a size of 2 × 3 m for each tree. This construction was waterproof and sufficiently large to create a totally precipitation-exclusive environment. All of the tents were fixed using several 30-cm iron nails inserted into the ground to prevent wind damage (Figure 1).



**Figure 1.** Schematic structure of the drought experiment and selected trees of *Tilia cordata* and *Tilia tomentosa*. The rooting zones of trees covered by the rainfall exclusion constructions were the drought treatment group, whereas trees exposed to ambient weather conditions for the control group.

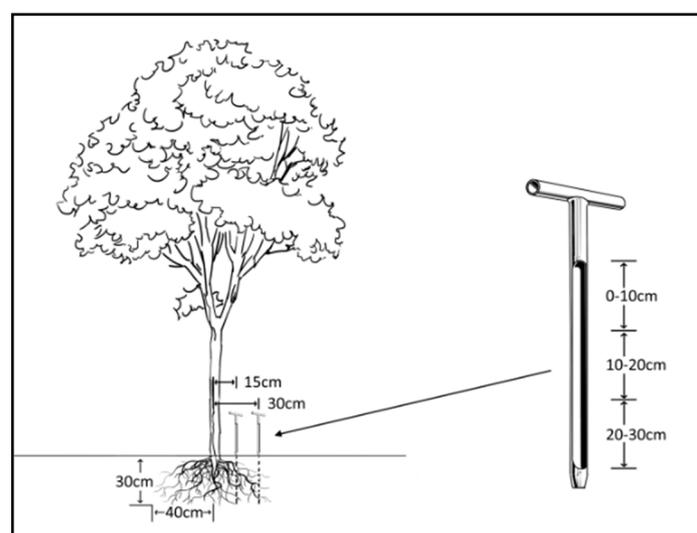
#### 2.4. Stem Growth and Leaf Area Index (LAI)

The diameter at a height of 1 m (nursery workers in Germany measure DBH at 1 m instead of 1.3 m) was measured using a digital caliper at the beginning of each month from April to November 2017. Measurements were conducted in two perpendicular directions (N–S, E–W) and averaged to account for irregularities in the form of the trunks. We focused on the relative rather than the absolute biomass increments to make the data independent of the initial biomass.

The leaf area index ( $\text{m}^2 \text{ m}^{-2}$ ; LAI) was determined using hemispherical photographs (Nikon Coolpix P5100 camera with a fisheye lens and Mid-OMount) and analyzed with the programme WinSCANOPY (Régent Instruments Inc., Quebec, QC, Canada). Data acquisition was performed under conditions of a uniformly overcast sky in the middle of June, shortly after implementation of the drought experiment.

#### 2.5. Coring for Fine Root Biomass

Fine root coring campaigns were launched for all trees in May, September, and November, i.e., at the beginning, middle, and end of the growing season. Due to the homogenous edaphic and climatic conditions in the nursery, we hypothesized that all the trees of the two cultivars had a similar growth condition. A pre-test coring campaign showed that the range of the root system was similar to a cylinder with a 70-cm diameter and 35-cm height. Therefore, during every coring campaign, four soil cores were collected for every individual tree, two at a distance of 15 cm to the trunk and the other two at a distance of 30 cm, i.e., the inner and outer fine roots. The soil was sampled down to a 30-cm soil depth using a soil auger with 30-cm length and 3-c-cm radius. Each sample was divided into three horizons: 0–10, 10–20, and 20–30 cm soil depth, i.e., the upper, middle, and lowest layers (Figure 2). Fine roots (<2 mm) were filtered using sieves (2-mm mesh size) and separated by forceps in the laboratory. Then, the samples were carefully washed and dried in the oven at 65 °C for 72 h. Finally, all the samples were weighed using a balance with an accuracy of four decimal digits to obtain the dry weight. Fine root biomass at different depths was calculated using the dry weight divided by the cross area of the auger.



**Figure 2.** Fine roots were analyzed in different vertical and horizontal levels by coring at distances of 15 and 30 cm from the trunk.

#### 2.6. Statistical Analysis

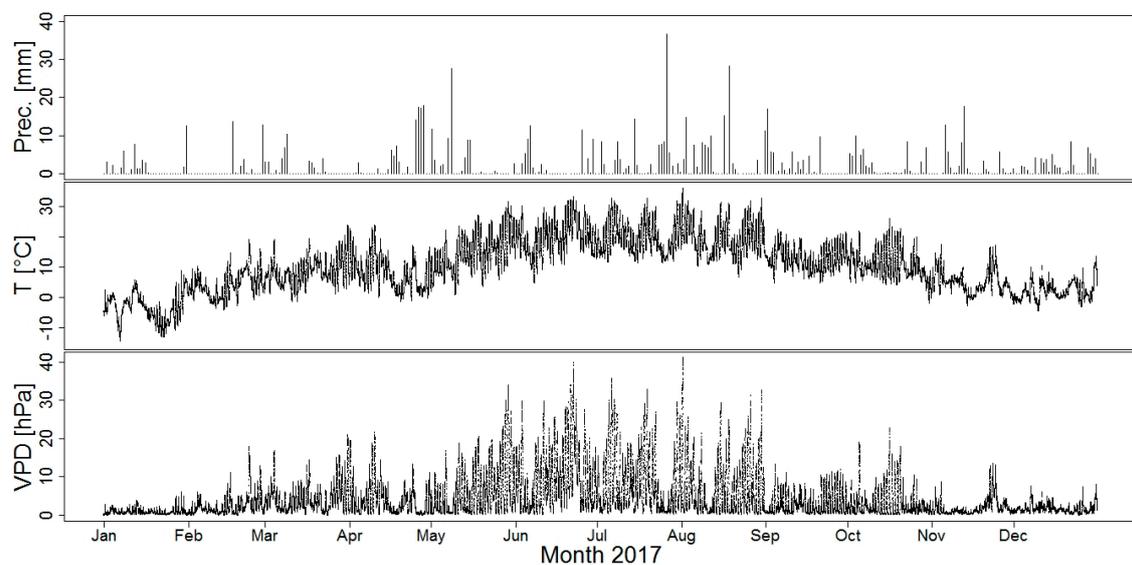
The software package R was used for statistical analysis [46]. To investigate the difference between means ( $n = 4$ ), two-sampled *t*-test and analysis of variance (ANOVA) with Tukey’s HSD test were used.

In all cases the means were reported as significant when  $p < 0.05$ . Where necessary, data were log or power transformed in order to correct for data displaying heteroscedasticity.

### 3. Results

#### 3.1. Weather and Soil Conditions

Precipitation varied clearly between April and November in 2017, the total sum of this period was 564 mm. July and August had relatively abundant precipitation reaching 102 and 123 mm, respectively. Other months were relatively dry, particularly during a 13-day period between 13 June and 25 June during which no rainfall was recorded. Precipitation started to increase at the beginning of May and showed a declining trend during early September. The site experienced a continuous warm period from 30 June to 30 August with 19.6 °C average daytime temperature (Figure 3).

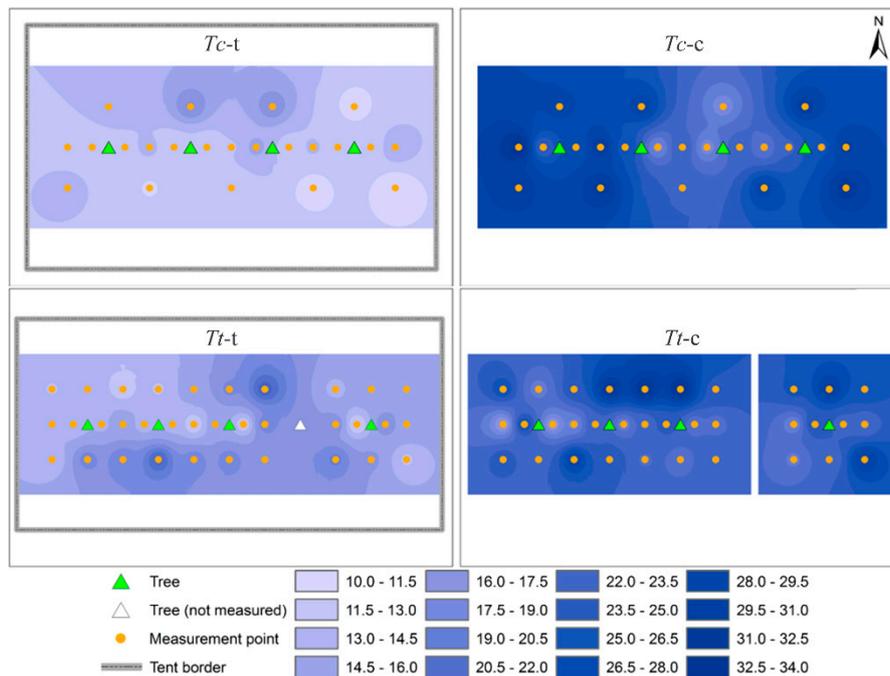


**Figure 3.** Daily amount of precipitation (Prec.; mm), temperature (T; °C), and the vapor pressure deficit (VPD; hPa) at the site for the year 2017.

For both the control and treatment groups of the two cultivars, all trees were grown in the same soil environment, which consisted mainly of medium sand (Table 1). In terms of the soil moisture, the drought treatment groups had significantly lower volumetric soil moisture contents (VWC; Vol.-%) in comparison to the control plots ( $p < 0.001$ ), with the roofed *T. tomentosa* showing the lowest average value of 19.4% (Figure 4). In addition, we found that the VWC 1 m from the trees, and therefore closer to the tent border, was significantly higher than that in the center of the roofs ( $p = 0.014$ ). Therefore, the data indicated the overall success of the drought experiment.

**Table 1.** Soil characteristics for both the control and drought treatment groups of *T. cordata* and *T. tomentosa*.

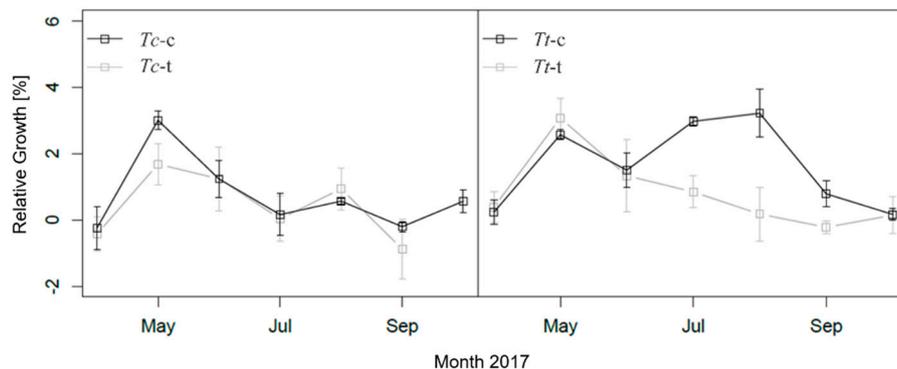
Group	n	Fine Sand %	Fine Silt %	Grit %	Coarse Grit %	Medium Sand %	Medium Silt %
Tc-c	4	15.8 ± 3.6	6.5 ± 1.1	9.0 ± 2.2	16.0 ± 1.2	27.3 ± 4.9	8.7 ± 3.3
Tc-t	4	22.6 ± 5.9	3.8 ± 1.3	7.7 ± 4.3	12.2 ± 2.7	33.4 ± 4.7	8.1 ± 1.3
Tt-c	4	14.2 ± 0.4	5.7 ± 2.5	11.2 ± 0.7	10.8 ± 2.3	23.7 ± 1.8	14.0 ± 4.3
Tt-t	4	14.0 ± 0.7	7.3 ± 0.9	11.6 ± 0.5	12.7 ± 2.3	23.1 ± 2.0	11.2 ± 1.0



**Figure 4.** Maps (interpolated values) of the volumetric soil water contents (Vol.-%; VWC) at a soil depth of 10 cm averaged over four measurement days in summer 2017 and collected at defined distances from the study trees. The rooting zones of the tree individuals in the respective left graphics were covered by the rainfall exclusion constructions (‘drought treatment’,  $T_c-t$  and  $T_t-t$ ), whereas the individuals in the right images belonged to the control groups (‘control’,  $T_c-c$  and  $T_t-c$ ).

### 3.2. Relative Stem Growth and LAI

For both cultivars, stem growth in the control and treatment groups reached a peak during May. After rapid growth during late spring, a tendency of decreased growth toward autumn for *T. cordata* from both the control and treatment groups with considerably similar patterns was obvious. In contrast, *T. tomentosa* individuals showed different developments between the control and drought treatment groups after June.  $T_t-c$  had strong growth until September, whereas  $T_t-t$  was strongly affected by the drought and showed a continuous growth decrease (Figure 5).



**Figure 5.** Monthly relative stem increment (%) of control and drought treatment groups of *T. cordata* and *T. tomentosa* from April to October 2017. Values denote the average of all trees per cultivar and group  $\pm$  the standard deviation.

*T. cordata* showed a quite fast development, i.e., this species unfolded its leaves earlier than *T. tomentosa* that did not unfold their leaves until the third week of May. In summer, LAI of  $T_c-t$  under drought was reduced in comparison to  $T_c-c$  ( $p < 0.05$ ) while an opposite pattern was found for *T.*

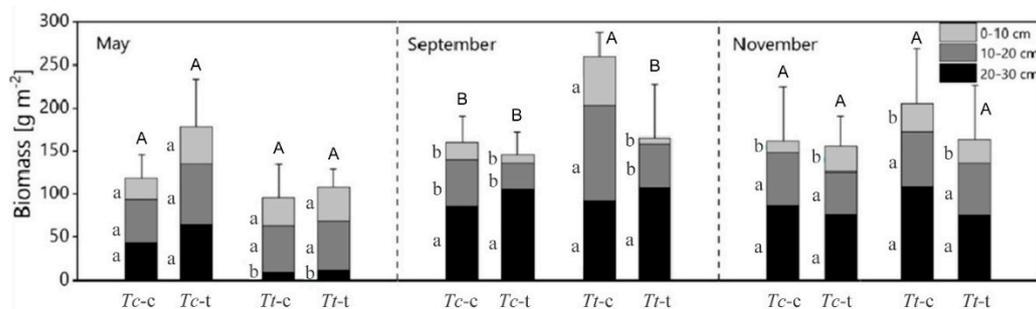
*tomentosa*, i.e., *Tt-t* was higher than *Tt-c* ( $p > 0.05$ ). In autumn, individuals of *Tc-t* were leafless in the middle of October while *T. tomentosa* had longer vegetation periods (Table 2).

**Table 2.** Leaf area index (LAI;  $\text{m}^2 \text{m}^{-2}$ ) of the two tree cultivars from both the control and treatment groups in June 2017.

Cultivar	Group	<i>n</i>	LAI ( $\text{m}^2 \text{m}^{-2} \pm \text{SD}$ )
<i>T. cordata</i>	Control	4	$2.53 \pm 0.49$
	Treatment	4	$2.13 \pm 0.48$
<i>T. tomentosa</i>	Control	4	$2.92 \pm 0.21$
	Treatment	4	$3.11 \pm 0.55$

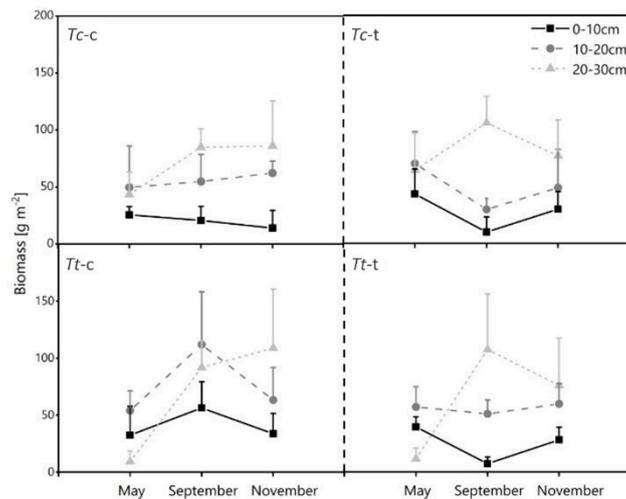
### 3.3. Total and Vertical Fine Root Biomass

Fine root biomass of the two cultivars was different from May to November. During the beginning of the growing season, *T. cordata* and *T. tomentosa* showed no significant difference between the control and drought treatment groups ( $P_{T. cordata} = 0.066$ ,  $P_{T. tomentosa} = 0.526$ ). The fine root biomass of *Tc-c* increased by 36.5% to  $161.4 \text{ g m}^{-2}$  from May to September and remained stable at  $162.2 \text{ g m}^{-2}$  from September to November, while that of *Tc-t* decreased by 18.1% to  $145.7 \text{ g m}^{-2}$  during the first four months (from May to September) but had a slight growth of 7.0% to  $155.8 \text{ g m}^{-2}$  during the last three months (from September to November). For *T. tomentosa*, the individuals of the control group behaved quite differently from the drought stressed group (Figure 6). The initial fine root biomass of the control and treatment groups was nearly similar at  $99.5$  and  $108.2 \text{ g m}^{-2}$ , but in the course of the experiment, *Tt-c* increased to  $259.8 \text{ g m}^{-2}$ , (161.2%) from May to September while *Tt-t* increased to  $165.6 \text{ g m}^{-2}$ . Over the period from September to November, *Tt-c* showed a remarkable decrease to  $205.7 \text{ g m}^{-2}$  while *Tt-t* remained at  $163.9 \text{ g m}^{-2}$ .



**Figure 6.** Fine root biomass ( $\text{g m}^{-2}$ ) for the 0–10, 10–20, and 20–30 cm layers of the control and treatment groups of *T. cordata* and *T. tomentosa* during May, September, and November 2017. The different letters indicate significant differences ( $p < 0.05$ ) between cultivars and treatments for the overall biomass (capital letters) and different layers (lowercase letters).

For vertical development, the fine root biomass in the three layers developed differently between the control and drought treatment groups of both cultivars (Figures 6 and 7). For *T. cordata*, fine root growth was observed highest in the 20–30 cm layer from May to September in the control group. In the drought treatment group, the fine root biomass from both the 0–10 and 10–20 cm layers sharply decreased by 77.1% and 57.4%, respectively. In the deep layer (20–30 cm) we observed contrasting development that it increased to a peak of  $105.8 \text{ g m}^{-2}$  during September and decreased to  $76.8 \text{ g m}^{-2}$  during November.

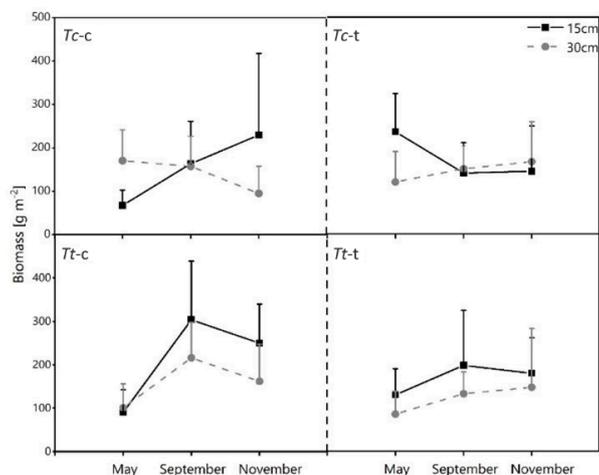


**Figure 7.** Fine root biomass ( $\text{g m}^{-2}$ ) in the three layers of 0–10, 10–20, and 20–30 cm of the control and drought treatment groups of *T. cordata* and *T. tomentosa* in May, September, and November 2017. Values denote the average of all trees per cultivar and group  $\pm$  the standard deviation.

For *T. tomentosa*, *Tt-c* continued growing in the 20–30 cm layer while the fine roots from the 0–10 and 10–20 cm layers decreased by 40.3% and 43.4%, respectively. For *Tt-t*, the fine root biomass in the three layers developed significantly differently from *Tt-c* during the whole period ( $p = 0.039$ ). In 0–10 cm depth the fine root biomass decreased from 39.5 to 7.3  $\text{g m}^{-2}$  during the first four months and increased to 28.2  $\text{g m}^{-2}$  during the last three months. The fine roots in the 10–20 cm layer showed only slight fluctuations for the whole period. The fine root biomass in the deep layer was initially very low (11.6  $\text{g m}^{-2}$ ) and steeply increased to 107.4  $\text{g m}^{-2}$  by September. In contrast, the same layer in the control group decreased by 29.3%.

### 3.4. Horizontal Development of Fine Root Biomass

The horizontal development of fine roots of the two cultivars was different when exposed to drought ( $p < 0.05$ ) (Figure 8). The fine root biomass of *Tc-c* steadily increased at a distance of 15 cm from the stem, whereas it decreased at a distance of 30 cm from May to November. *Tc-t* decreased its fine root biomass at a distance of 15 cm from 235.7 to 140.7  $\text{g m}^{-2}$  from May to September, whereas the biomass at a distance of 30 cm slightly increased over measurement time.



**Figure 8.** Horizontal development of fine root biomass ( $\text{g m}^{-2}$ ) at a distance of 15 and 30 cm of the control and treatment groups of *T. cordata* and *T. tomentosa* during May, September, and November 2017. Values denote the average of all trees per cultivar and group  $\pm$  the standard deviation.

For *T. tomentosa*, drought had an impact on the fine root growth from May to September. It reduced the fine root biomass by 23.7% at a distance of 15 cm and by 11.4% at a distance of 30 cm in the control groups, and by 52% and 55% in the treatment groups, respectively. From September to November, *Tt-c* decreased from 303.7 to 249.7 g m<sup>-2</sup> at a distance of 15 cm and from 215.9 g m<sup>-2</sup> to 161.6 g m<sup>-2</sup> at a distance of 30 cm, which had a similar trend in *Tt-t*.

#### 4. Discussion

In this study, we studied the fine root biomass of *T. cordata* and *T. tomentosa* cultivars in response to drought stress. We found different growth patterns under water shortage between the two cultivars in both the vertical and horizontal directions reflecting clear differences in the carbon allocation within a tree for the two cultivars.

##### 4.1. Total Fine Root Biomass

Effects of drought manipulations are very complex [47]. In this study, we found that drought had a relatively small impact on fine root growth of *T. cordata* and it invested less energy than *T. tomentosa* on belowground growth, the fine root biomass only slightly varied between control and drought treatment trees. Moser et al. [21] found that *T. cordata* showed a continued decrease in aboveground growth after a drought event while our results showed the congruent growth for belowground processes. This implies that the belowground part did not actively react to cope with drought stress.

In contrast, starting from May *T. tomentosa* showed a vigorous fine root growth in both control and drought treatment groups, i.e., *T. tomentosa* invested or gave the priority to the belowground growth. Radoglou et al. [48] also found that *T. tomentosa* with sufficient water supply reacts dynamically with fine root growth. Under water shortage, our results showed that the fine root biomass growth of *Tt-t* decreased compared to *Tt-c* from May to September, however, there was still a distinct growth over the whole growing season. Combined with the results of Stratópoulos et al. [49], *T. tomentosa* originating from dry regions was proved to be a drought-resistant species that could cope well with water shortage. Based on our observations, the main strategy of *T. tomentosa* could be the steady and continuous investment in the belowground growth under drought stress, which could prove the vitality of the fine roots of *T. tomentosa* undertook the ability of water absorption in response to the dry environment.

##### 4.2. Vertical Development of Fine Root Biomass

Despite the fact that the total fine root biomass of the control and treatment groups for *T. cordata* trees were similar, the fine root biomass of the three layers showed different patterns. *Tc-c* exposed to normal conditions slowly increased their growth in the deep layer and decreased it in the upper layer, which was consistent with previous results [50,51]. However, in response to drought, the fine root biomass in the upper and middle soil layers of *Tc-t* sharply decreased. Simultaneously, the deep fine roots of *Tc-t* developed stronger than the fine roots of *Tc-c* probably to obtain water from deeper soil parts. During autumn (from September to November), the fine root development in all the soil layers was completely different compared to summer. The deep roots decreased whereas the roots in the upper and middle soil layer initiated growth. Accounting for the steady total fine root biomass, the preferential development of fine roots in different soil layers may reflect specific allocation to soil layers with reserve water over the course of the season. Gillner et al. found that *T. cordata* recovered after decreasing growth resulting from a drought event, which could be explained by the resumptive growth of the fine roots in the upper and middle soil layers [52]. Less energy was invested by *T. cordata* in the belowground processes in all the soil layers to obtain enough growth, especially during a drought event. This might lead to a growth balance between the shallow and deep fine roots.

For *T. tomentosa*, without a water shortage, fine roots vigorously developed in all the soil layers of the control group during the first four months, whereas it was different for the upper and middle layers in the dry treatment group. The roots in the middle layer showed no growth and the shallow roots almost died because of the drought. However, simultaneously the deep fine roots exhibited

strong growth, which was even higher than the growth in the control group. This was considered as an essential step to adapt to drought. During autumn, for both the control and treatment groups, the fine roots in each layer had opposite growth patterns than those earlier in the season. We did not only observe that the shallow roots had a similar growing tendency to that of the fine roots in the middle layer but also found a dynamic balance for all fine roots, in the way that if the fine roots in the upper and middle layer increased or decreased, the deep fine roots decreased or increased accordingly.

Recent research has shown that deep roots can be of pivotal importance to alleviate water stress in many plants [53]. They particularly play a central role in drought tolerance in tropical and subtropical environments [54]. Our results proved this with the development of the deep fine roots of *T. tomentosa*, which originated from drier regions than those of *T. cordata*. Schenk proposed that the rooting profiles of plant communities tended to be as shallow as possible and as deep as needed to meet the evapotranspiration demand [55]. The idea is that plants need less energy for the construction of shallow roots than of deep roots, although the balance of allocation of carbon to roots and the acquisition of water are central to tree survival. Moreover, soil close to the surface can provide high water and nutrient availability for root growth most of the time. In addition, shallow soils have lower soil strength, which usually avoids the possibility of oxygen deficiency for the roots. Generally, the growth of deep roots can even be a drain for downward hydraulic redistribution [56].

During the beginning of drought events, however, deep roots can uptake more water which is an advantage compared with a shallow rooting system because lower maintenance costs tend to counter-balance the high construction costs of deep roots [57,58]. Fine root turnover increases with soil depth because the roots are probably strongly modulated by a combination of environmental factors, e.g., soil moisture and texture [59,60]. In the study of Stratópoulos et al. [49], *T. tomentosa* showed strong resistance against drought whereas *T. cordata* performed negatively. In this study, the fine roots of *T. cordata* showed a minor reaction to drought. *T. tomentosa*, however, developed new fine roots in the vertical direction especially in the deep soil layers in summer, which could be regarded as an effective solution in coping with drought stress. Moreover, when the availability of water was high, *T. cordata* did not show vigorous growth, whereas *T. tomentosa* developed abundant deep roots which probably aimed to prevent the risk of drought damage.

#### 4.3. Horizontal Development of Fine Root Biomass

Different tree species have different distribution patterns of fine roots in the horizontal direction [51]. Similarly, we found that under normal conditions fine root development of *T. cordata* was more stem-centered whereas *T. tomentosa* showed no priority for inner root growth. Under drought stress, this tendency was reversed. The outermost fine roots did not decrease any further, whereas the inner fine roots died because of water shortage. This could be a strategy of *T. cordata* trees to expand their root system to acquire more water by decreasing the support of the fine roots at a distance of 15 cm. For the *T. tomentosa* individuals of the control group, both the inner and outer fine roots underwent similar growth from May to November, which was also found for the trees in the treatment group. Both the fine roots of *T. tomentosa* in the control and treatment groups had an increase in innermost area during the first four months and a decrease in outermost fine root biomass during the last three months. This implies that drought did not affect horizontal expansion and no priority was given to the fine roots in horizontal direction.

#### 4.4. Carbon Allocation under Drought Stress

Figure 5 displays that the relative stem growth of both *T. cordata* and *T. tomentosa* reached the peak in May which is similar to the results of Rahman et al. [61]. In general, annual stem growth predominantly occurs from May to July [62]. During this period, temperature and water availability are the main determining factors for radial growth [52,63]. However, for different tree species and cultivars, the patterns can be distinct [52]. We found similar trends in stem development for *T. cordata* in the control and drought treatment groups during the whole growing season. This could be explained

by the mechanism of anisohydric behavior, i.e., that *T. cordata* reduced leaf water potential under drought stress [64]. There was no significant difference in the stem and root growth between the control and drought treatment groups, because the high levels of stomatal conductance preserved stem and root growth [65]. For *T. tomentosa*, the stem growth in the drought treatment group decreased compared with that in the control group. However, the fine root biomass simultaneously developed strongly, which implied that *T. tomentosa* prioritized belowground processes to obtain water under drought stress.

## 5. Conclusions

We found that the fine root growth showed different responses to drought stress in two cultivars widely planted in Europe. We hypothesized that both the two cultivars had a similar initial growth condition and the development of their fine root could reflect the underground strategy. *T. cordata* trees showed little growth that similar growth patterns for stem and total fine root biomass were observed under drought stress. However, increased outer fine roots for horizontal expansion could be the potential reason for its living. For *T. tomentosa*, it invested more on roots, particularly deep roots in order to absorb water, which suggests a strategy of prioritizing belowground processes regarding the decrease of the stem growth. In conclusion, the two cultivars displayed different reactions to water shortage that *T. cordata* tended to support the expansion of fine roots horizontally while *T. tomentosa* is assumed to develop deep fine roots.

Thus, under the background of global change with higher temperatures, altered precipitation patterns, and more extreme weather events (e.g., drought), city planners should consider providing enough space when planting trees in streets and squares. The development of fine roots of urban trees should be considered when planting urban trees. The horizontal expansion of fine roots of some tree species and cultivars could alleviate water shortages; however, this could result in damage to pavements. This suggests the necessity of sufficient space for tree species and cultivars such as *T. cordata* 'Greenspire'. Tree species and cultivars with an active reaction to drought stress could be prioritized in urban management. Those with a deep root strategy such as *T. tomentosa* 'Brabant' could be an appropriate and economic choice as they are adaptable to drought stress. Long-term observations of fine root growth patterns are needed to provide more in-depth information and quantify the root development of different trees species and cultivars in urban surroundings.

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