

Article

Patterns in Tree Cavities (Hollows) in Euphrates Poplar (*Populus euphratica*, Salicaceae) along the Tarim River in NW China

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Abstract: *Populus euphratica* Oliv., an indicator species for eco-environmental change in arid areas, plays a key role in maintaining the stability of fragile oasis–desert ecosystems. Owing to human interference as well as to the harshness of the natural environment, *P. euphratica* forests have suffered severe damage and degradation, with trunk cavities (i.e., hollows) becoming increasingly pronounced, and thus posing a great threat to the growth, health, and survival of the species. Currently, there is a gap in our understanding of cavity formation and its distribution in *P. euphratica*. Here, cavities in the trunks and branches of a *P. euphratica* in a typical transect (Arghan) along the lower Tarim River were studied based on field positioning observations combined with laboratory analysis. The results revealed a large number of hollow-bearing *P. euphratica* stands in the study area; indeed, trees with hollows accounted for 56% of the sampled trees, with approximately 159 trees/ha. Sixty-six percent of hollow trees exhibited large ($15\text{ cm} \leq \text{cavity width (CW)} < 30\text{ cm}$) or very large ($\text{CW} > 30\text{ cm}$) hollows. The main types of cavities in the trees were trunk main (31.3%), trunk top (20.7%), branch end (19.5%), and branch middle (19.5%). Tree parameters, such as diameter at breast height (DBH), tree height (TH), east–west crown width (EWCW), height under branches (UBH), and crown loss (CL) were significantly different between hollow and non-hollow trees. Both cavity height and width were significantly and positively correlated with DBH and CL, as well as with average crown width (ACW) ($p < 0.001$) and the distance from the tree to the river. The proportion of *P. euphratica* trees with cavities showed an overall increasing trend with increasing groundwater depth. Our findings show that cavities in *P. euphratica* varied with different tree architectural characteristics. Water availability is a major environmental factor influencing the occurrence of hollowing in desert riparian forests. The results provide scientific support for the conservation and sustainable management of existing desert riparian forest ecosystems.

Keywords: functional degradation; tree hollow; adaptation strategy; environmental stress; *Populus euphratica*



Citation: Aishan, T.; Mumin, R.; Halik, Ü.; Jiang, W.; Sun, Y.; Yusup, A.; Chen, T. Patterns in Tree Cavities (Hollows) in Euphrates Poplar (*Populus euphratica*, Salicaceae) along the Tarim River in NW China. *Forests* **2024**, *15*, 421. <https://doi.org/10.3390/f15030421>

Academic Editor: Akira Itoh

Received: 21 December 2023

Revised: 8 February 2024

Accepted: 19 February 2024

Published: 22 February 2024



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1. Introduction

Tree stems connect the roots and crown and have major transporting and supporting functions [1,2]. Cavities or hollows in the trunk of a tree reduce its mechanical stability [3]. The distribution of cavities or hollows in living trees varies among forest types and under different site conditions within any given forest stand [4–9]. A tree is classified as hollow- or cavity-bearing if it contains at least one hollow in its trunk or branches [6]. Furthermore, studies have shown that there are significantly more or fewer decay hollows in tree trunks in certain specific environments (humidity, diseases, drought, etc.), and that

the formation and development of hollow decay in tree trunks are greatly affected by the specific site conditions [10–12]. Therefore, understanding the relationship between hollow formation or cavity occurrence in living trees and site conditions is necessary to inform forest conservation and sustainable management.

As the main body of the natural riparian vegetation in the inland river basins of Northwestern China, Euphrates poplar (*Populus euphratica*, Salicaceae) stands constitute an ecological corridor that constitutes the regional biodiversity hotspot and has the highest bioproductivity in the region [13,14]. These forests play a key role in maintaining the structure and function of riparian ecosystems in arid areas, acting as natural barriers to protect oasis agriculture and livestock production from the adverse impacts of desertification. However, in the particularly arid region of Tarim River Basin, owing to the excessive utilization of water and soil resources and anthropogenic disturbances such as deforestation over the past 50 years, natural vegetation habitats dominated by *P. euphratica* have been continuously lost. Specifically, in this region, natural oases have been shrinking, lakes have been drying up or disappearing, and desertification has increased. The natural *P. euphratica* desert forest ecosystems distributed on both banks of the lower reaches of the Tarim River have experienced dry flow for nearly 30 years, which has caused serious damage to the ecosystem [15,16].

As an indicator species of regional environmental change, *P. euphratica* riparian forests adapt their growth and development in response to biotic and abiotic stresses in different ways, including certain unique strategies that developed over evolutionary time to respond to extreme environments [17]. For example, *P. euphratica* trees grow a well-developed horizontal root system and heteromorphic leaves in response to drought stress [18]; additionally, the species responds to salt stress through selective absorption and the storage of salt ions in the body [19]. In disconnected rivers and areas with a low soil moisture content, self-renewal occurs through clonal reproduction by root suckering [20]. Moreover, *P. euphratica* exhibits a phenomenon that is easily overlooked, namely cavity or hollow formation in tree trunks.

Study have shown that, as the age of trees increases, the probability of hollow formation in the trunk also increases [21]. In addition, the degree or rate of tree hollowness is allegedly affected by its specific environment; thus, trees have a defense system against internal decay in the trunk [22]. Further, tree growth is affected by changes in site conditions, resulting in different extents of tree cavity formation [23]. Therefore, from the perspective of site conditions, researching the characteristics of hollow-bearing tree trunks would facilitate an understanding of the reasons for hollow formation and provide scientific evidence to support developing protective measures for existing natural *P. euphratica* forest resources. To date, studies in this field remain scarce, and the reasons for hollow formation and their influencing factors remain unclear [24,25]. In particular, in extremely arid habitats with strong wind erosion, *P. euphratica* forests are exposed to strong winds, rendering hollow-bearing trees susceptible to breakage and collapse [26]. A clearer understanding of the patterns of tree cavities/hollow in *P. euphratica* forests can provide basic data for urgently needed protection measures. In this study, we investigated the quantitative characteristics and distribution patterns of cavities in *P. euphratica* trees and attempted to answer the following scientific questions: What is the relationship between hollows and tree architectural characteristics? What is the influence of groundwater depth on the formation of cavities in *P. euphratica* trees? Our findings provide a useful update on the ecology of hollow *P. euphratica* and a scientific reference for maintaining and managing desert riparian forest ecosystems in arid regions.

2. Materials and Methods

2.1. Study Site

The study area is located along the Arghan transect (40°08′50″ N, 88°21′28″ E), between the Taklamakan and Kuruk Tag Deserts, in the lower reaches of the Tarim River, Xinjiang Uyghur Autonomous Region, Northwest China (Figure 1). This area is located in

an extremely arid climatic zone, with an average annual precipitation of <15 mm [13,14] and a potential annual evaporation of 2500–3000 mm [15,16]. Sparse vegetation comprising trees, shrubs, and herbs is predominantly distributed in river floodplain ecosystems. *Populus euphratica* is the dominant tree species in the study area, where nearly 70% of the existing plant species are *P. euphratica* trees [14]. Shrubs include *Tamarix ramosissima* Ledeb., *Tamarix hispida* Willd., *Tamarix elongata* Ledeb., *Lycium ruthenicum* Murr., *Halimodendron halodendron* (Pall.) Voss., *Halostachys caspica* (M.B.) C.A. Mey, *Poa cynosuroides* (Hook. F.) Woodson., *Alhagi sparsifolia* (B. Keller et Shap.) Shap., *Glycyrrhiza inflata* Bat., *Karelinia caspica* (Pall.) Less, *Inula salsoloides* (Turcz.) Ostrnf., and *Hexinia polydichotoma* (Ostenf.) H.L. Besides *Tamarix*, most trees, shrubs, and herbs are distributed within the buffer zone at a distance of 100 m from the river. In particular, owing to the scarcity of precipitation, groundwater is the main source of the water required to maintain the structure and function of riparian ecosystems in this hyper-arid region.

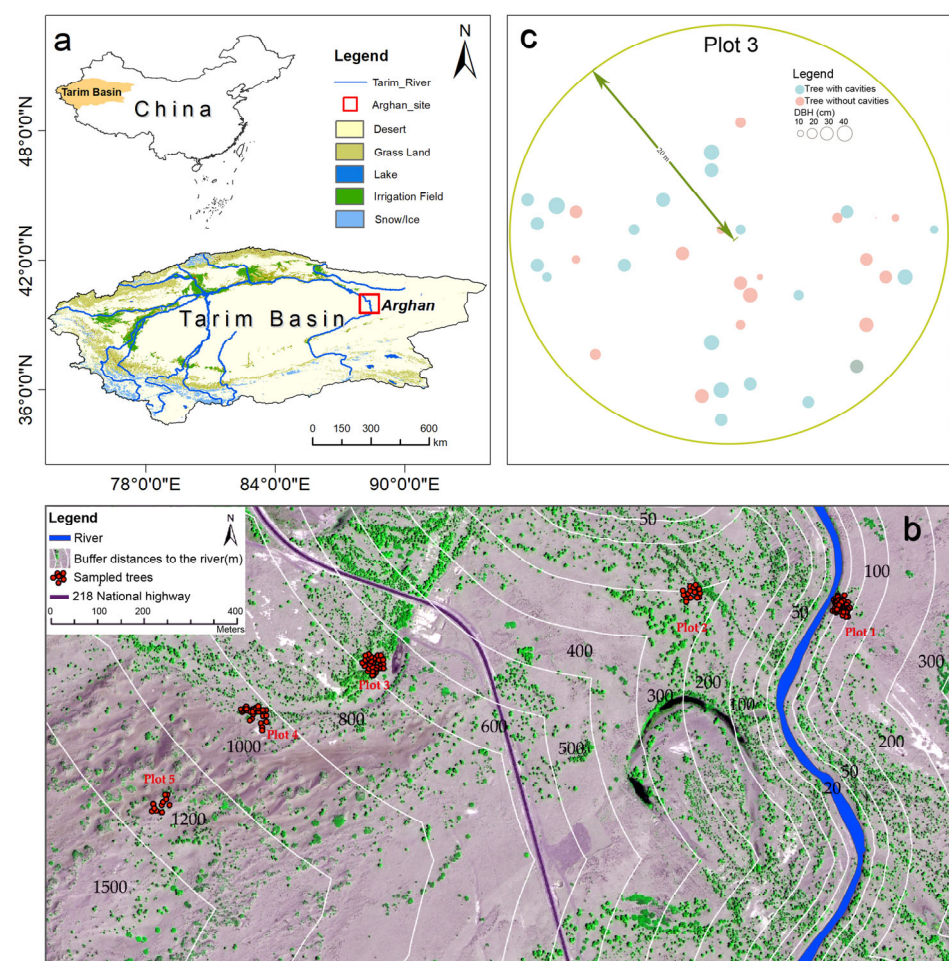


Figure 1. Map showing the location of the study site in the Tarim Basin, northwest China. (a) The study area in the lower reaches of the Tarim River is highlighted in the red rectangle; (b) the distribution of five sampled plots (plots 1–5) in the study area; (c) the distribution of trees with and without cavities in plot 3.

2.2. Data Collection and Processing

2.2.1. Plot Design and Measurements

Given the spatial heterogeneity of water conditions and the principle of representativeness, in August 2020 and July 2021, five circular plots with radii of 20 m at different distances from the river (≤ 20 , 20–200, 200–500, 500–750, and 750–1050 m) were established at the Arghan Transect in the lower reaches of the Tarim River. The smallest diameter at

breast height (DBH) of hollow trees was used as a selection criterion: a tree-hollow survey was conducted for all *P. euphratica* trees with a DBH ≥ 5 cm in each plot (Figure 2). *P. euphratica* trees with one or more tree cavities on the trunk and branches were defined as hollow trees, and their related tree architectural characteristics, including DBH, tree height (TH), south–north crown width (SNCW), east–west crown width (EWCW), average crown width (ACW), height under branch (HUB), and crown loss (CL), as well as tree cavity characteristics, including the number of tree hollows, cavity types, cavity orientation, cavity height, and cavity width, were measured and recorded. The DBH of each tree was measured using a DBH meter (accuracy < 0.1 cm) and TH and HUB were determined using a laser distance meter. The SNCW and EWCW of the tree canopy were measured with a measuring tape, and the average was calculated as the ACW. The CL, with the values for an ideal tree and a completely withered tree taken as 0% and 100%, respectively, was estimated according to Aishan et al. [13]. Referring to survey methods [6] used for hollow trees, tree hollows with good visibility were counted and their parameters were measured directly from ground level, while tree hollows distributed on the higher parts of trunks or canopy branches were observed using binoculars (10×25). Cavity orientation was determined using a compass. The tree geographical location and the number of trees in the sample plot were recorded. Tree cavities were divided into seven types according to their location and shape: butt hollow, trunk main, trunk top, fissure, branch middle, branch end, and bayonet. The hollow size was grouped into one of four size classes based on cavity width: small (< 5 cm), medium (5–15 cm), large (15–30 cm), and very large (> 30 cm). In addition, partial sapwood/heartwood samples were taken from healthy and decayed tree trunks using an increment borer (Haglof, Langsele, Sweden). The presence or absence of animal utilization of tree holes was also recorded. The proportion of hollow trees (%) was the proportion of trees with hollows among all trees sampled within a plot. Hollow tree density was the total number of hollow trees per unit area of forest land (trees/ha). Groundwater depth data were obtained from the long-term monitoring wells installed by the Tarim River Basin Administration and BARO-Diver (DI800, vanEssen, Delft, The Netherlands) and set up by our research team.

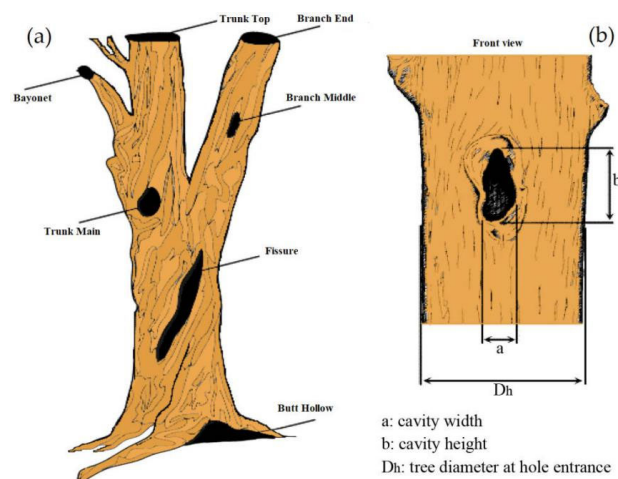


Figure 2. Cavity types and measurements; (a) location and type of cavities in trees, modified from [26]; (b) measured parameters of cavities, modified from [27].

2.2.2. Data Processing and Analysis

A map showing the location of the research area and the distribution pattern of trees with plots was created using ArcGIS 10.0 software (Esri, Inc., Redlands, CA, USA) based on a GIS database established by integrating QuickBird images with terrestrial field survey data. A schematic illustration of the cavity types was produced using Photoshop 2017 (Adobe Inc., San Jose, CA, USA). Differences in architectural characteristics among the three groups (hollow, non-hollow, and all) were tested using one-way ANOVA (significance

level of $p = 0.001$) in SPSS 19.0 (IBM Corp., Armonk, NY, USA). Box-whisker plots and pie charts were produced using Origin9.4 software (OriginLab, Northampton, MA, USA). The Mantel test and random forest analyses were performed to evaluate the relationship between the cavity characteristics and tree attributes and establish the importance of factors influencing *P. euphratica* tree cavities using the “linkET” and “random forest” packages, respectively, and the results were visualized using the “ggplot2” package in R 4.2.3 (<https://cran.r-project.org/web/packages/ggplot2/index.html>, accessed on 13 May 2023).

3. Results

3.1. Cavity Types and Distribution Patterns

The frequency of hollow trees and number of holes in the selected sample plots indicated the characteristics of hollow trees and the abundance of holes in the study area (Table 1 and Figure 3). A total of 175 trees were investigated in the Arghan section, of which 98 (i.e., 56% of the total number of trees surveyed) were found to contain different types of hollows. A total of 352 tree holes were found in 175 trees, with densities ranging from 16 to 130 per sample plot and an average of 2.01 holes per tree. The proportions of each hollow type relative to the total number of holes were as follows: trunk main (31.3%), trunk top (20.7%), branch end (19.5%), branch middle (19.5%), butt hollow (5.1%), fissure (2.8%), and bayonet (1.1%). Holes classified as trunk main (31.3%) were significantly more abundant than the other six types of holes; the numbers of holes categorized as trunk top, branch end, and branch middle were not significantly different from each other ($p > 0.05$); and the proportions of holes categorized as butt hollow, fissure, and bayonet were smaller. These results indicate that holes are easily formed in the middle and top of the trunk and that more holes occur in the lateral branches of the middle and top sections.

Table 1. Descriptive statistics for tree attributes and tree cavity types in sample plots (mean $\pm$ SE).

Attributes at Tree and Cavity Levels	Sample Plot				
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Number of trees (n)	42	26	41	55	11
Distance from the river (DR) (m)	DR $\leq$ 20 m	20 < DR $\leq$ 200 m	200 < DR $\leq$ 500 m	500 < DR $\leq$ 750 m	750 < DR $\leq$ 1050 m
Number of trees with cavities (n)	11	14	21	41	11
Proportion of hollow trees (%)	26.20	53.80	51.20	74.50	100
Tree density (n/ha)	334	207	326	438	88
Mean tree height (m)	8.20 $\pm$ 2.0	7.10 $\pm$ 1.41	7.52 $\pm$ 2.13	5.54 $\pm$ 2.12	4.30 $\pm$ 1.33
Mean DBH (cm)	28.50 $\pm$ 8.90	35.42 $\pm$ 18.80	25.93 $\pm$ 8.51	29.91 $\pm$ 14.93	74.90 $\pm$ 30.20
Mean crown width (m)	7.20 $\pm$ 1.90	8.50 $\pm$ 2.00	7.13 $\pm$ 1.81	6.60 $\pm$ 1.73	6.30 $\pm$ 2.31
Mean crown loss (%)	12.3 $\pm$ 12.0	29.2 $\pm$ 0.2	26.0 $\pm$ 0.1	33.0 $\pm$ 0.2	67.0 $\pm$ 0.1
Number of butt hollows (n)	0	2	3	8	5
Number of fissures (n)	0	3	0	3	4
Number of trunk main holes (n)	4	14	11	42	36
Number of branch middle holes (n)	6	9	12	8	34
Number of branch end holes (n)	1	13	3	20	33
Number of bayonet holes (n)	0	1	1	1	1
Number of trunk top holes (n)	5	6	6	39	17

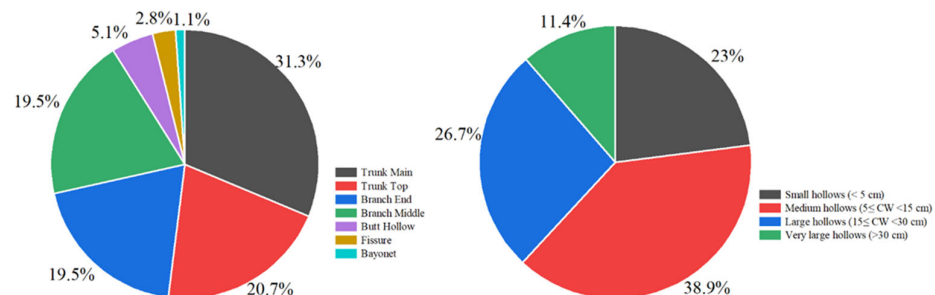


Figure 3. Percentages of hollow types and sizes found at all sites (CW: cavity width).

3.2. Architectural Traits of Trees with and without Hollows

The *P. euphratica* trees surveyed in the study area were divided into two groups according to the presence of hollows: hollow-bearing and non-hollow-bearing trees (Figure 4). The results showed that the DBH, TH, EWCW, HUB, and CL of hollow-bearing trees were

significantly different between the groups ($p < 0.001$), whereas other indices did not differ significantly. Similarly, significant differences ($p < 0.001$) were also observed for the DBH, TH, EWCW, HUB, and CL of non-hollow-bearing versus hollow-bearing trees, indicating that hollowing in *P. euphratica* trees is also related to the tree architectural characteristics. Furthermore, the DBH, EWCW, and CL of trees with hollows were larger than those of trees without hollows. For most of the trees, particularly those classified as having very large hollows (>30 cm), the height and width of the cavities increased with increasing DBH. The DBH reflects the age of *P. euphratica* [28], and the cavities formed in older trees experienced more disturbance and took longer to form, suggesting that older *P. euphratica* forests are more susceptible to cavities. However, both the TH and the HUB of living *P. euphratica* with hollows were lower than those of trees without hollows, suggesting that the taller the tree, the less likely it is to form new cavities.

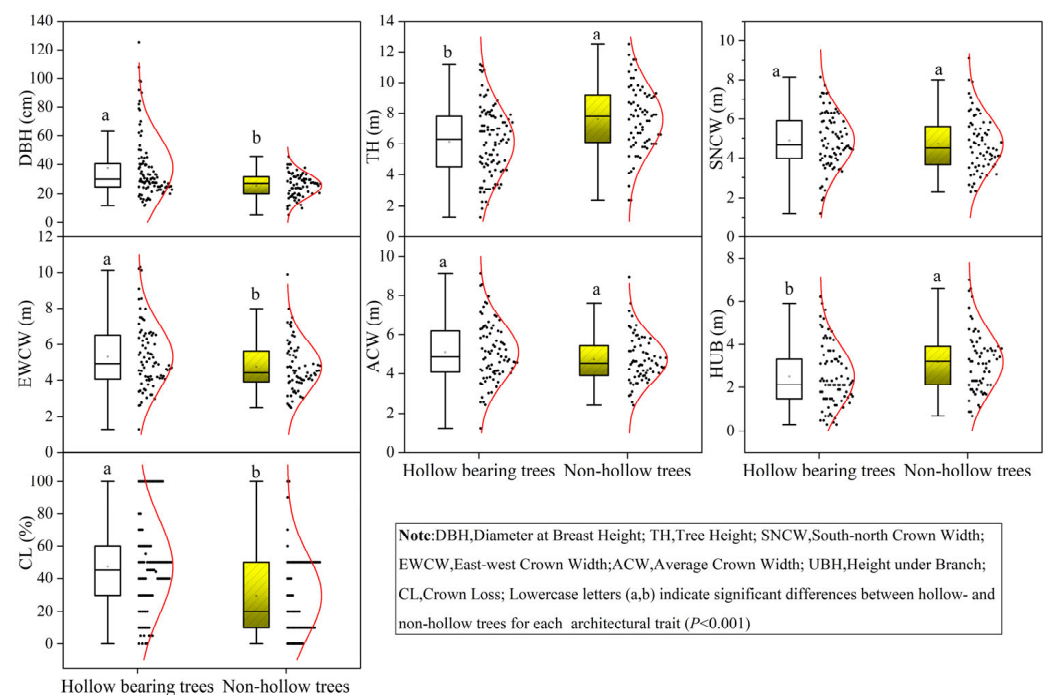


Figure 4. Architectural characteristics of hollow-bearing and non-hollow-bearing trees.

3.3. Relationship between Tree Attributes and Cavity Parameters

Figure 5 shows the results of the Mantel tests for the relationships between cavity characteristics, tree attributes, and water availability, with the orange color indicating highly significant ($p < 0.01$), green indicating significant ($p \leq 0.05$), and gray indicating non-significant ($p \geq 0.05$) relationships. As shown in Figure 5, tree cavity height showed a highly significant positive correlation ($p < 0.01$) with DBH and CL. Cavity width showed a highly significant positive correlation ($p < 0.01$) with DBH and CL and a significant negative correlation ($p \leq 0.05$) with TH. Among these variables, DBH and CL showed a highly significant positive correlation with tree cavity length and width ($p < 0.01$), indicating that DBH and CL were the main factors affecting the cavity height and width of *P. euphratica* trees, while DBH had a greater influence on tree cavity width. Random forest analysis was conducted to further investigate the correlation between the occurrence of cavities in *P. euphratica* and various tree architectural characteristics (Figure 6a,b). The results in Figure 6 show that DBH, average crown width, CL, and EWCW were more important in determining the height and width of cavities than any other variable. Random forest analysis thus showed that DBH was the most significant factor influencing the variation in both the height and width of *P. euphratica* cavities ($p < 0.001$).

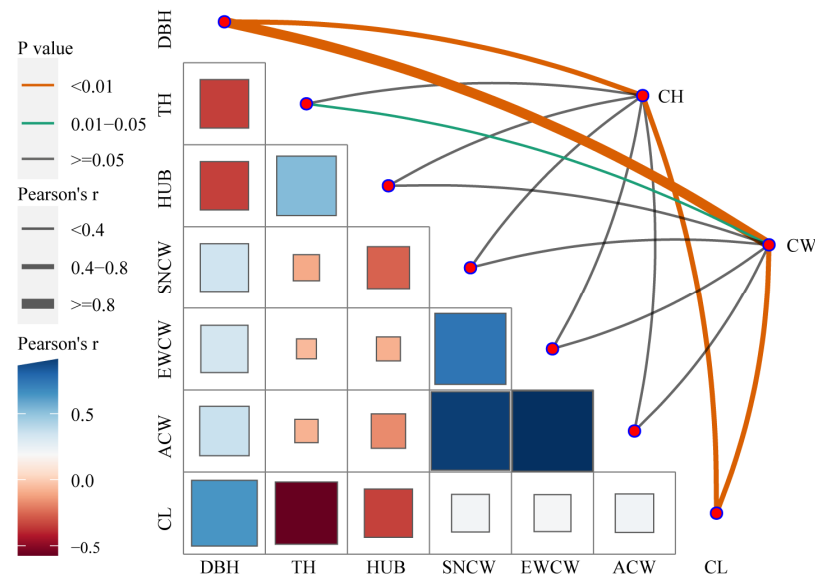


Figure 5. Mantel test results for the relationship between cavity characteristics and tree attributes (CH, cavity height; CW, cavity width; DBH, diameter at breast height; TH, tree height; HUB, height under branch; SNCW, south–north crown width; EWCW, east–west crown width; ACW, average crown width; CL, crown loss).

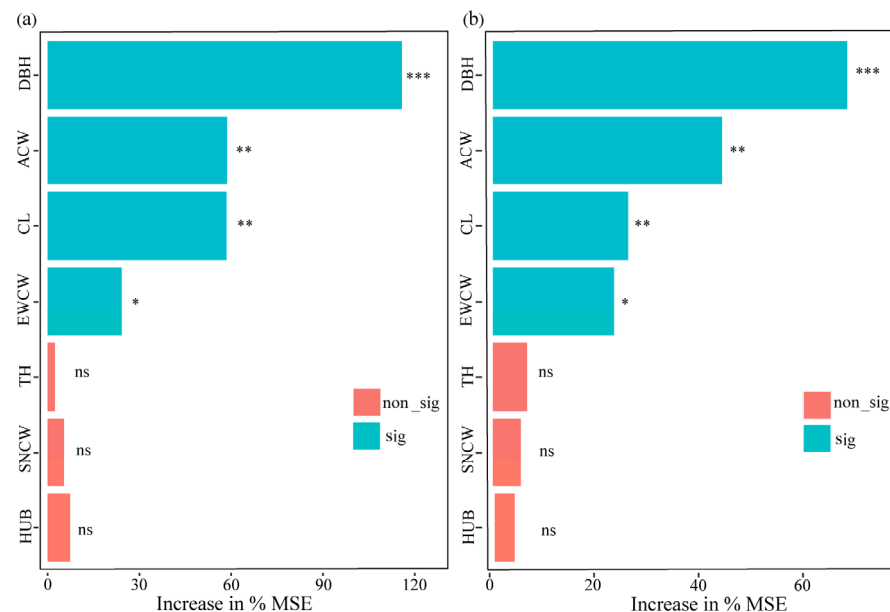


Figure 6. Importance of factors influencing *P. euphratica* tree cavities, as measured by the percentage increase in mean square error (MSE) in the random forest analysis; (a) presents the results of the random forest model for cavity height (CH); (b) results of the random forest model for cavity width (CW), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.4. Relationship between Water Availability and Cavity Parameters

As *P. euphratica* desert riparian forests survive in extremely arid environments, water accessibility (distance to the river and groundwater) is one of the most important environmental factors affecting plant growth and development. As a result, this study hypothesized that water conditions were likely to be the main factors influencing the formation of cavities in *P. euphratica* trees. Therefore, this paper seeks to elucidate the relationship between water conditions and the characteristics of hollow-bearing *P. euphratica* trees by studying and comparing the characteristics of hollow-bearing trees among *P. euphratica* populations at different locations (distance from the river) in relation to water resources.

Figure 7 shows the responses of the cavity parameters (CW and CH) of trees to variations in distance from the river. As shown in Figure 7, as the distance from the river increased, the cavity width and cavity height of *P. euphratica* showed significant variations ($p < 0.001$); near the river (<600 m), changes in cavity width and cavity height of *P. euphratica* were not apparent, but farther from the river (>600 m), the cavity width and cavity height of *P. euphratica* tended to increase. The overall trend indicated that the development of tree cavities was influenced, to some extent, by the distance of the trees from water resources. Figure 8 shows that there was a significantly positive correlation between the proportion of trees with cavities and groundwater depth ($r = 0.98$, $p < 0.01$).

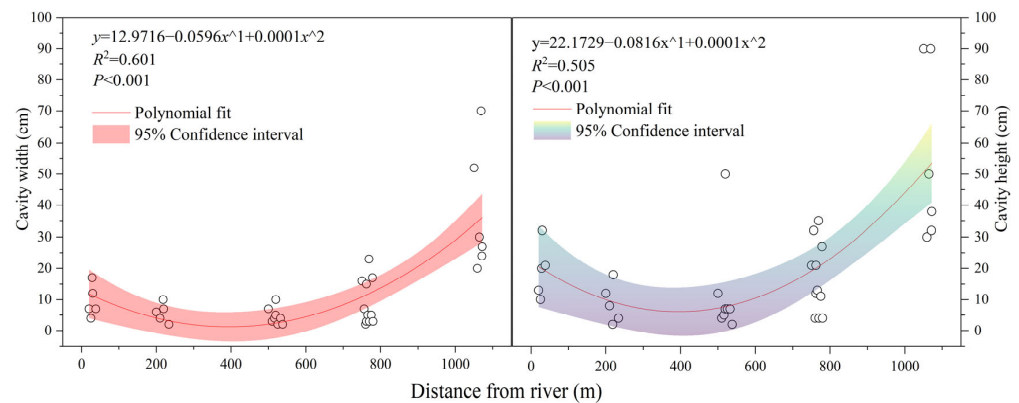


Figure 7. Variations in cavity parameters with distance from the river.

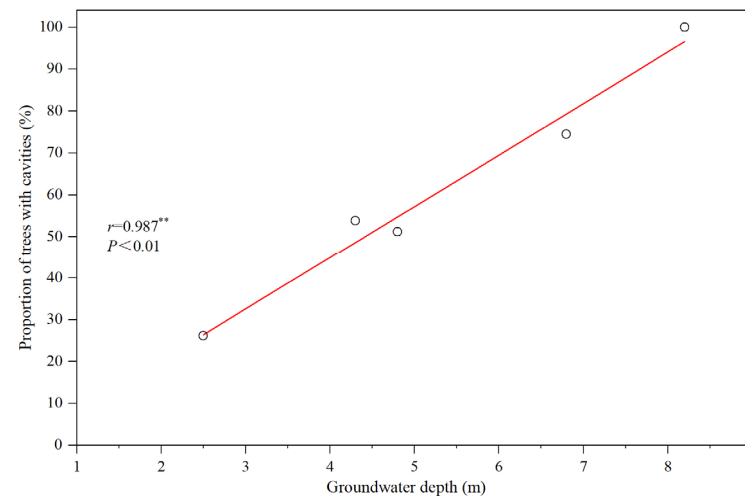


Figure 8. Relationship between proportion of hollow-bearing trees and groundwater depth (note: annual average groundwater depth data were used for this plot; **: significant correlation).

4. Discussion

Populus euphratica forests are likely to contain a high proportion of trees with hollows, with a hollow-bearing-tree density of 159 tree/ha, which is much higher than those of tropical seasonal rain forests (87 trees/ha), tropical mountain evergreen broad-leaved forests (approx. 86 trees/ha), subtropical humid evergreen broad-leaved forests (94.3 trees/ha), and even desert riparian forest in the middle reaches of the Tarim River (78 trees/ha) in China [25,29–31]. *Populus. euphratica* forests in this area are primeval, and most are over-matured [14] and contain numerous trees with hollows. External factors, such as sandstorms, strong winds, and long-term river desiccation, may cause hollows to form more easily in *P. euphratica* forests, resulting in different densities of hollow-bearing trees in different locations. Further, factors such as water conditions (mainly groundwater depth), desertification, and human interference also significantly influence the growth

and distribution pattern of natural vegetation in the Tarim River Basin [13,14]. Therefore, water availability is likely the key environmental factor affecting the formation of tree cavities. In this study, the presence of cavities in *P. euphratica* increased significantly with increasing DBH and decreased significantly with increasing TH. Owing to the extremely arid conditions in the lower Tarim River, the vertical growth of most *P. euphratica* forests is limited by water; thus, lateral growth is dominant [14]. Therefore, taller trees are likely to be distributed in areas with favorable water conditions, as well as be less exposed to water stress and maintain normal growth. Temperature is the main limiting factor in tropical rainforests, and the specific orientation of tree hollows is related to thermal conditions (such as the angle of the sun) [32]. In this study, 82 (23.4%) of the hollow-bearing trees sampled exhibited clear signs of broken stems or branches. In desert riparian forests, factors such as water availability and strong winds may lead to differences in the distribution patterns of tree cavities. Hollow-bearing trees provide critical microhabitat resources for forest fauna and play an important role in maintaining biodiversity [33,34]. Of the 352 tree holes sampled, only 3 (0.85%) exhibited signs of animal use; hence, almost no tree holes were used as animal habitats. Compared with other forest types, *P. euphratica* desert riparian forests are characterized by a simple community structure and relatively poor biodiversity. Therefore, the relationship between *P. euphratica* tree cavities and biodiversity was not quantified or further analyzed in the present study.

In the study area, most of the hollows were observed on *P. euphratica* trunks that had been blown down by wind or had broken branches. The formation of tree hollows may also be an indicator of *P. euphratica* senescence. In addition, we observed that *P. euphratica* stored large amounts of water in the trunk; it can be assumed that this storage would make the middle of the trunk susceptible to porosity and eventually lead to cavity formation. The more severe drought conditions become, the more likely a *P. euphratica* trunk will develop empty spaces by storing water. Therefore, the formation of tree holes in the trunk may also be a strategy of *P. euphratica* to adapt to extreme drought conditions. In addition, our study reveals that the height and width of *P. euphratica* cavities are significantly correlated with the distance from the river. As groundwater depth increased, the proportion of hollow-bearing trees in *P. euphratica* stands increased from 26.2% to 100%. *P. euphratica* trees, as phreatophytes (i.e., plant species that have evolved the capacity to access groundwater), mainly depend on groundwater to survive [14]. As shallow soil water sources are gradually depleted with increasing distance from the river, the depth and proportion of water uptake by phreatophytes from groundwater typically increases [35–37]. Therefore, phreatophytes develop deeper roots to track the capillary fringe and/or saturated zone of aquifers. Thus, groundwater depth is considered a key limiting factor that regulates stand structure and function in desert riparian forests. The habitat conditions of the lower Tarim River are more challenging than those of the upper and middle reaches, with frequent river-flow disconnections and deeper groundwater tables; all together, these conditions cause continuous water stress and also cause *P. euphratica* forests to develop an association between increasing tree age, declining tree function, and greater hollowing. Therefore, habitat quality, particularly with respect to water availability, is an important factor in the hollowing of *P. euphratica* forests.

The formation of hollow trees is a slow and complex process that is influenced by a combination of factors, including the habitat conditions of the forest and the characteristics of the trees themselves. Hollowing is the end result of decay in living trees, with some trees forming hollows gradually from the inside out and exhibiting large external holes that are visible to the naked eye, and others starting directly from the outside, with various decay fungi invading the sapwood exterior. This study identified several issues that need to be investigated and addressed in future research. For example, drilling samples of heartwood and sapwood revealed that some of the trunks were extensively decayed internally and that the heartwood was decayed or in a crumbly state. Consequently, quantitative studies of internal decay in living trees are needed, and characteristics such as the decay ratio, decayed area, volume, and decay orientation need to be quantified using

high-precision non-destructive instrumentation, such as Arbotom stress-wave detection and TreeRadar [2,38–40]. In addition, this study was mainly concerned with the physical parameters of the trees and thus can be improved by the addition of chemical (biochemical) parameters at a later stage. Therefore, it is expected that this aspect will be thoroughly investigated in depth in future studies.

5. Conclusions

We investigated and analyzed the characteristics of hollow trees in natural *P. euphratica* stands at different distances (water stress) from the lower Tarim River and concluded that the *P. euphratica* population in the study area had a high degree of hollowing, with living trees with hollows accounting for 56% of the total number of trees surveyed and large and trees with very large hollows in turn accounting for nearly 66% of hollow-bearing trees sampled. In addition, hollowing in *P. euphratica* trees was closely related to tree architectural characteristics, indicating that hollowing also affects the growth pattern of *P. euphratica* to some extent. The frequency of hollowing increased with increasing DBH. Furthermore, both the cavity width and the cavity height of *P. euphratica* showed a tendency to increase with increasing distance from the river, and the proportion of trees with cavities showed an increasing trend with increasing groundwater depth. Based on the results of our study, we propose that the elevation of groundwater at a distance from the river and optimization of stand age structure through ecological water delivery can decrease the occurrence of hollows in *P. euphratica* forests.

Author Contributions: All authors contributed to the design and development of this manuscript. T.A. and R.M. conducted the research and prepared the first draft of the manuscript; Ü.H. conceived and designed the overall concept of the research, supervised, and participated in the fieldwork; W.J. and Y.S. provided important advice and technical support on the methodology; T.A., R.M., A.Y., T.C. collected and processed the data. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (Grant Nos. 32160367 and 32260285) and the Third Xinjiang Scientific Expedition and Research Program (Grant No. 2022xjkk0301).

Data Availability Statement: The datasets used in this study are available upon request. Please contact the first author if you are interested in this study.

Acknowledgments: We thank the Tarim River Basin Administration Bureau for providing hydrological data and the Forestry Department of Qarkilik (Ruoqiang) for logistical support during our field work in Arghan. The authors are grateful to the anonymous reviewers for their constructive comments. The authors thank colleagues from Xinjiang University for helping with collecting and processing the data.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tsutomu, U.; Masato, S.; Akio, K.; Hiroyuki, T.; JooYoung, C. Both stem and crown mass affect tree resistance to uprooting. *J. For. Res.* **2012**, *17*, 65–71.
2. Wei, Z.C.; Halik, U.; Aishan, T.; Abliz, A.; Welp, M. Spatial distribution patterns of trunk internal decay of Euphrates poplar riparian forest along the Tarim River, northwest China. *For. Ecol. Manag.* **2022**, *522*, 120434. [[CrossRef](#)]
3. Marra, R.E.; Brazee, N.J.; Fraver, S. Estimating carbon loss due to internal decay in living trees using tomography: Implications for forest carbon budgets. *Environ. Res. Lett.* **2018**, *13*, 105004. [[CrossRef](#)]
4. Niringiyimana, A.; Nzarora, A.; Twahirwa, J.C.; van der Hoek, Y. Density and characteristics of tree cavities inside and outside Volcanoes National Park, Rwanda. *Ecol. Evol.* **2022**, *12*, e9461. [[CrossRef](#)] [[PubMed](#)]
5. LaMontagne, J.M.; Kilgour, R.J.; Anderson, E.C.; Magle, S. Tree cavity availability across forest, park, and residential habitats in a highly urban area. *Urban Ecosyst.* **2015**, *18*, 151–167. [[CrossRef](#)]
6. Harper, M.J.; McCarthy, M.A.; van der Ree, R. The abundance of hollow-bearing trees in urban dry sclerophyll forest and the effect of wind on hollow development. *Biol. Conserv.* **2005**, *122*, 181–192. [[CrossRef](#)]
7. Fan, Z.F.; Shifley, S.R.; Spetich, M.A.; Thompson, F.R.; Larsen, D.R. Distribution of cavity trees in midwestern old-growth and second-growth forests. *Can. J. For. Res.* **2003**, *33*, 1481–1494. [[CrossRef](#)]

8. Liu, J.Y.; Zheng, Z.; Xu, X.; Dong, T.F.; Chen, S.C. Abundance and distribution of cavity trees and the effect of topography on cavity presence in a tropical rainforest, southwestern China. *Can. J. For. Res.* **2018**, *48*, 1058–1066. [\[CrossRef\]](#)
9. Takashima, A.; Nakanishi, A.; Morishita, M.; Abe, S.; Saito, K.; Kotaka, N. Tree-cavity formation in the mature subtropical forests of Yambaru, Okinawa Island. *J. For. Res.-Jpn.* **2021**, *26*, 410–418. [\[CrossRef\]](#)
10. Soge, A.O.; Popoola, O.I.; Adetoyinbo, A.A. Detection of wood decay and cavities in living trees: A review. *Can. J. For. Res.* **2021**, *51*, 937–947. [\[CrossRef\]](#)
11. Jauregui, A.; Rodriguez, S.A.; Garcia, L.N.G.; Gonzalez, E.; Segura, L.N. Wood density and tree size used as cues to locate and excavate cavities in two Colaptes woodpeckers inhabiting a threatened southern temperate forest of Argentina. *For. Ecol. Manag.* **2021**, *502*, 119723. [\[CrossRef\]](#)
12. Dudinszky, N.; Ippi, S.; Kitzberger, T.; Ceron, G.; Ojeda, V. Tree size and crown structure explain the presence of cavities required by wildlife in cool-temperate forests of South America. *For. Ecol. Manag.* **2021**, *494*, 119295. [\[CrossRef\]](#)
13. Peng, Y.; He, G.J.; Wang, G.Z. Spatial-temporal analysis of the changes in *Populus euphratica* distribution in the Tarim National Nature Reserve over the past 60 years. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *113*, 103000.
14. Aishan, T. Degraded Tugai Forests under Rehabilitation in the Tarim Riparian Ecosystem, Northwest China: Monitoring, Assessing and Modelling. Ph.D. Thesis, Katholische Universitat Eichstätt-Ingolstadt, Eichstätt, Germany, 2016; 152p.
15. Ling, H.B.; Guo, B.; Zhang, G.P.; Xu, H.L.; Deng, X.Y. Evaluation of the ecological protective effect of the “large basin” comprehensive management system in the Tarim River basin, China. *Sci. Total Environ.* **2019**, *650*, 1696–1706. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Ling, H.B.; Zhang, P.; Xu, H.L.; Zhao, X.F. How to Regenerate and Protect Desert Riparian *Populus euphratica* Forest in Arid Areas. *Sci. Rep.* **2015**, *5*, 15418. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Zhuang, L.; Li, W.H.; Yuan, F.; Gong, W.C.; Tian, Z.P. Ecological adaptation characteristics of *Populus euphratica* and *Tamarix ramosissima* leaf microstructures in the lower reaches of Tarim River. *Acta Ecol. Sin.* **2010**, *30*, 62–66. [\[CrossRef\]](#)
18. Li, D.; Si, J.H.; Zhang, X.Y.; Gao, Y.Y.; Luo, H.; Qin, J.; Ren, L.X. Ecological adaptation of *Populus euphratica* to drought stress. *J. Desert Res.* **2020**, *40*, 17–23. (In Chinese)
19. Zhao, R.; Chen, S.L. The salt-stress signaling network involved in the regulation of ionic and ROS homeostasis in poplar. *Sci. Sinica Vitae* **2020**, *50*, 167–175. (In Chinese)
20. Eusemann, P.; Petzold, A.; Thevs, N.; Schnittler, M. Growth patterns and genetic structure of *Populus euphratica* Oliv. (Salicaceae) forests in NW China—Implications for conservation and management. *Forest Ecol. Manag.* **2013**, *297*, 27–36. [\[CrossRef\]](#)
21. Renton, K.; Salinas-Melgoza, A.; Rueda-Hernandez, R.; Vazquez-Reyes, L.D. Differential resilience to extreme climate events of tree phenology and cavity resources in tropical dry forest: Cascading effects on a threatened species. *Forest Ecol. Manag.* **2018**, *426*, 164–175. [\[CrossRef\]](#)
22. Vazquez, L.; Renton, K. High density of tree-cavities and snags in tropical dry forest of western Mexico raises questions for a latitudinal gradient. *PLoS ONE* **2015**, *10*, e0116745. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Onodera, K.; Tokuda, S.; Abe, T.; Nagasaka, A. Occurrence probabilities of tree cavities classified by entrance width and internal dimensions in hardwood forests in Hokkaido, Japan. *J. Forest Res.-Jpn.* **2013**, *18*, 101–110. [\[CrossRef\]](#)
24. Mumin, R.; Aishan, T.; Halik, U. Hollow-bearing characteristics of *Populus euphratica* in the lower reaches of Tarim River, China. *Chin. J. Appl. Ecol.* **2020**, *31*, 1933–1940. (In Chinese)
25. Cheng, Q.; Aishan, T.; Halik, U.; Wang, X.Y. Hollow tree characteristics of different aged *Populus euphratica* forests in the middle reaches of the Tarim River. *Arid Zone Res.* **2023**, *40*, 247–256. (In Chinese)
26. Li, Z.W.; Yu, G.A.; Brierley, G.J.; Wang, Z.Y.; Jia, Y.H. Migration and cutoff of meanders in the hyperarid environment of the middle Tarim River, northwestern China. *Geomorphology* **2017**, *276*, 116–124. [\[CrossRef\]](#)
27. Lindenmayer, D.B. Cavity sizes and types in Australian eucalypts from wet and dry forest types—A simple of rule of thumb for estimating size and number of cavities. *Forest Ecol. Manag.* **2000**, *137*, 139–150. [\[CrossRef\]](#)
28. Wang, S.J.; Chen, B.H.; Li, H.Q. *Populus euphratica* Forest; China Environmental Science Press: Beijing, China, 1995; pp. 57–59. (In Chinese)
29. Remm, J.; Löhms, A.; Remm, K. Tree cavities in riverine forests: What determines their occurrence and use by hole-nesting passerines? *Forest Ecol. Manag.* **2006**, *221*, 267–277. [\[CrossRef\]](#)
30. Wang, Y.T.; Xu, H.D.; Wang, L.H.; Li, F.R.; Sun, H. Field investigation of decay rate of Korean pine standing trees in natural forests in Lesser Xing’an Mountains. *J. Beijing For. Univ.* **2015**, *37*, 97–104. (In Chinese)
31. Brandeis, T.J.; Newton, M.; Filip, G.M. Cavity-nester habitat development in artificially made Douglas-fir snags. *J. Wildl. Manag.* **2002**, *66*, 625–633. [\[CrossRef\]](#)
32. Boyle, W.A.; Ganong, C.N.; Clark, D.B. Density, distribution, and attributes of tree cavities in an old-growth tropical rain forest. *Biotropica* **2008**, *40*, 241–245. [\[CrossRef\]](#)
33. Gruebler, M.U.; Schaller, S.; Keil, H.; Naef-Daenzer, B. The occurrence of cavities in fruit trees: Effects of tree age and management on biodiversity in traditional European orchards. *Biodivers. Conserv.* **2013**, *22*, 3233–3246. [\[CrossRef\]](#)
34. Ibarra, J.T.; Novoa, F.J.; Jaillard, H.; Altamirano, T.A. Large trees and decay: Suppliers of a keystone resource for cavity-using wildlife in old-growth and secondary Andean temperate forests. *Austral Ecol.* **2020**, *45*, 1135–1144. [\[CrossRef\]](#)
35. Thomas, F.M. Ecology of phreatophytes. *Prog. Bot.* **2014**, *75*, 335–375.
36. Thomas, F.M.; Jeschke, M.; Zhang, X.; Lang, P. Stand structure and productivity of *Populus euphratica* along a gradient of groundwater distances at the Tarim River (NW China). *J. Plant Ecol.* **2017**, *10*, 753–764.

37. Si, J.H.; Feng, Q.; Cao, S.K.; Yu, T.F.; Zhao, C.Y. Water use sources of desert riparian *Populus euphratica* forests. *Environ. Monit. Assess* **2014**, *186*, 5469–5477. [[CrossRef](#)] [[PubMed](#)]
38. Goh, C.L.; Rahim, R.A.; Rahiman, M.H.F.; Talib, M.T.M.; Tee, Z.C. Sensing wood decay in standing trees: A review. *Sensor Actuat. A Phys.* **2018**, *269*, 276–282. [[CrossRef](#)]
39. Li, H.B.; Zhang, X.W.; Li, Z.Q.; Wen, J.; Tan, X. A Review of Research on Tree Risk Assessment Methods. *Forests* **2022**, *13*, 1556. [[CrossRef](#)]
40. Okun, A.; Brazee, N.J.; Clark, J.R.; Cunningham-Minnick, M.J.; Burcham, D.C.; Kane, B. Assessing the Likelihood of Failure Due to Stem Decay Using Different Assessment Techniques. *Forests* **2023**, *14*, 1043. [[CrossRef](#)]

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