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Performances of Urban Tree Species under Disturbances in 120 Cities in China

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Abstract: Selecting tree species for urban greening requires a good understanding of the performance of the species under different types of disturbances. However, information on performances of many species is still not available today. In this study, we used an extensive data set gathered through a systematic literature review to analyze the impacts of five major types of disturbances on urban tree species in China. Our results showed that there were distinctive spatial patterns of occurrences of these disturbances on urban trees. Urban trees in north China were mainly disturbed by low temperature, snow, and wind. In central China, low and high temperatures were major disturbances. Urban trees in south China suffered greatly from low temperature and wind. Pests and disease were reported more frequently in east China, where most cities are located. Of the 1010 taxa of trees reported over the 120 cities in the study—which included 723 taxa identified to the species level, 264 identified to the sub-species level, and 23 identified to the genus level—the impacts of these disturbances varied widely. We recommend that cities reduce or avoid the use of tree species that perform poorly under these disturbances.

Keywords: urban forest; species selection; disturbance; susceptibility; damage

1. Introduction

As more than half of the world's population now live in cities, urban forests play an important role in creating livable environments for a huge number of people. Urban forests can generate ecosystem services that are essential for urban residents' wellbeing, such as removal of air pollutants [1], reduction of urban floods [2], alleviation of urban heat islands [3], and provision of recreational opportunities [4]. Because of these important benefits, cities worldwide are investing resources to maintain existing urban forests and create new ones.

A healthy and functional urban forest is the basis for sustainable production of ecosystem services. Species diversity is important for maintaining the health of urban forests. Studies have shown that urban forests with good species diversity are more resilient to disturbances in urban environments such as extreme weather events and pests and diseases [5]. Species diversity is also key to the generation of different types of ecosystem services. For example, wildlife in urban environments require certain tree species as food sources or shelters [6]. Species that can tolerate water-logging are needed for projects that deal with urban stormwater [7]. In addition, people in general prefer urban forests with good species diversity for recreational uses [8]. Due to these reasons, researchers and practitioners are looking for ways to increase species diversity of urban forests [9–11].

Nevertheless, it is not a good practice to increase species diversity of urban forests by simply adding more tree species. Tree species used in cities should be able to tolerate common urban environmental stresses such as compacted soils and pollution [12,13]. They should also be resilient to disturbances such as extreme weather events and pests and diseases. Wrong choices can lead to significant economic and ecological losses. For example, the extensive use of American elm (*Ulmus americana* L.) in North American cities led to the devastation of street tree populations in these cities when the Dutch elm disease attacked this species [14]. The replacement of American elm with ash trees (*Fraxinus* spp.) in many cities then paved the way for infestation by emerald ash borers [15]. Extreme weather events also frequently inflict damages on urban forests planted with poorly selected species. For instance, in Lianyungang City, China, a cold spell in 2016 damaged 40,000 camphor trees (*Cinnamomum camphora* (L.) J. Presl) [16]. Extreme weather events are predicted to occur more often in the future due to climate change [17]. Because of their long life spans, trees planted today will be subjected to the impacts of the future climate. The risk of significant loss can be high [18]. Thus, practitioners have to keep future risks in mind when adding new tree species. One solution is to assess the performance of planted trees under different types of disturbances and use the information to inform practitioners on selecting tree species. Although there are limitations associated with this approach, e.g., the existence of many confounding factors, the approach can at least provide a coarse estimate of the sensitivity of tree species to different types of disturbances.

China offers an excellent opportunity to study the performance of tree species in urban environments under different types of disturbances. In the past four decades, China has experienced rapid urbanization. The urbanization rate has increased from 17.9% in 1978 to 56.1% in 2015 [19]. The acreage of built-up areas also has increased from less than 10,000 km^2 to 52,100 km^2 [20]. Along with the expansion of cities, green spaces in cities are also increasing. A study found that green coverage in built-up areas of 32 major cities increased from 17.28% to 23.88% between 1990 and 2010. The increase of green coverage is largely due to new plantings [21]. During this period, cities all over China have planted a large number of trees. For example, just in Beijing, about 50 million trees have been planted between 2012 and 2014 [22]. To keep up with the fast pace of urban greening, many tree species that have not been well tested in their intended planting sites are used. This practice equals to a large-scale "trial" of tree species in urban environments. Therefore, to summarize lessons learned in this trial in a timely manner cannot only help cities in China to select right trees for right places but can also contribute to the general knowledge of the performance of urban tree species under different types of disturbances.

In this study, we conducted a systematic assessment on performances of tree species under major types of disturbances in cities in China. Specifically, we have the following objectives: (1) to identify patterns of occurrences of disturbances on urban forests in China, and (2) to find out tree species that are sensitive to these disturbances.

2. Methods

2.1. Data Collection

We conducted a systematic literature review by following the PRISMA approach [23]. We ran a search using both international (Scopus and the Web of Science) and domestic (China National Knowledge Infrastructure and Wanfang Data) databases. The following topic search was used:

(urban OR city) AND (tree OR "woody plant") AND species AND (drought OR storm OR cold OR "low temperature" OR "high temperature" OR "sunburn" OR wind OR disease OR pest OR snow OR sleet OR ice OR hail OR rain* OR typhoon) AND (symptom OR damage OR injury OR death OR wilt OR defoliage OR split OR broken OR overthrown OR uproot* OR tilt*) AND (LIMIT-TO (AFFILCOUNTRY, "China"))

Publications retrieved from these databases include journal articles, dissertations, and conference proceeding papers. We performed the initial screening of the retrieved publications based on their titles and abstracts. Only papers that presented study results on impacts of disturbances on urban trees were kept for further analysis. Then a more detailed review was conducted to exclude publications that did not contain lists of species and descriptions of impacts caused by disturbances. We then extracted out names of species and descriptions of impacts caused by disturbances from the selected publications and merged all information into a data set for further analysis.

2.2. Data Analysis

We used a qualitative approach to analyze the impacts of different types of disturbances on urban tree species using the data set gathered through the systematic literature review. We tallied the total number of species impacted by a specific type of disturbance, the number of cities that reported the disturbance, and occurrences of a specific type of disturbance. We also identified species that were susceptible to a specific type of disturbance. We took into consideration the severity of impact and the geographic region where the disturbance occurred.

We summarized the impacts of high temperature into two categories: drought stress and sunburn. High temperature often joins with inadequate soil water supply to cause drought stress on urban trees. Sunburn mainly occurs on trunks of urban trees, especially near the base. The strong solar radiation heats the trunk and the soil surface and causes damage to trunks [24].

To analyze the impacts of low temperature on urban tree species, we first divided cities into three groups based on their geographic location. The first group includes cities that are located north of the 40° N latitude line. The second group includes cities that are located south of the 30° N latitude line. The third group includes cities that fall in between 30° N and 40° N. We used this classification because temperate tree species in north and central China and subtropical and tropical tree species in south China are susceptible to different low-temperature ranges.

Winds that caused damage on urban trees in China include strong winds and typhoons. We summarized the reported wind damages into five categories, including broken branches, canopy loss, broken stems, tilting, and uprooting.

We separated damages caused by snow into three types: cold injuries, waterlogging, and mechanical injuries (including defoliation, broken branches, broken stems, tilting, and uprooting). Waterlogging mainly happens in the spring when snow piled around trees melts.

We summarized impacts of plant diseases by tree species and types of diseases. Major types of diseases include leaf diseases, branch/stem diseases, root diseases, and systemic diseases. We summarized the number of species that each type of disease influenced. We analyzed the impacts of pests in a similar way.

3. Results

3.1. Results of the Systematic Literature Search

Through the systematic literature search, we found 1805 publications initially. After going through titles and abstracts, we kept 658 publications that reported disturbances on urban trees for detailed review. Among them, 144 publications contained detailed information of species and their responses to different disturbances. The materials were published between 1979 and 2017.

We extracted out 4836 records for 120 Chinese cities from these 144 publications. In total, these records contained information for 1010 taxa of trees, which include 723 species, 264 taxa at sub-species level, and 23 taxa that were only identified to the genus level.

3.2. The General Pattern of Occurrences of Disturbances on Urban Forests in China

In our compiled data set, 21 cities reported damages caused by high temperature on 143 taxa of trees. Low temperature caused damages on 847 taxa of trees in 51 cities. Wind damages occurred on 190 taxa of trees in 23 cities. About 53 cities reported diseases and pests on trees, which included 62 types of diseases and 252 taxa of pests. These diseases and pests affected 288 taxa of trees. Damages caused by snow affected the least number of cities and trees; only nine cities reported damages on 102 taxa of trees (More information is available in the supplementary data file). Hereafter we refer to all taxa as species for ease of communication, but readers should keep in mind that the species mentioned afterward include trees at sub-species level and those only identified to the genus level.

3.3. Impacts Caused by Low and High Temperatures

Damages on trees caused by high temperature were mainly reported by cities in central China, such as Chongqing, Hefei, Nanjing, and Changsha (Figure 1). A few cities in north China such as Wuwei and Beijing also reported this disturbance. The range of temperatures reported in literature were between 35 °C and 42.9 °C, with a mean value of 38 °C.

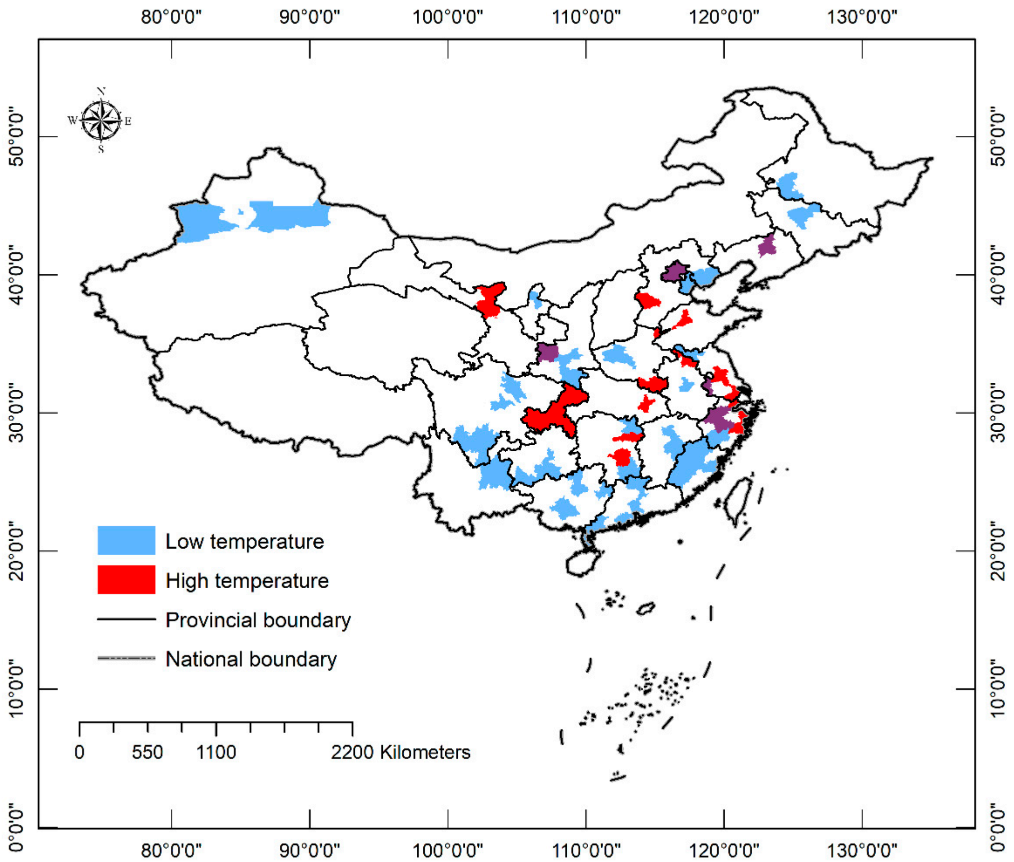

Figure 1. Spatial patterns of damages on urban trees caused by low and high temperatures in China. Cities that reported both types of damages appear as purple color due to the overlap.

The two major types of damages caused by high temperature—drought stress and sunburn—affected almost the same number of species, 88 and 90, respectively (Table 1). However, drought stress occurred more frequently and in more cities.

Table 1. Summary of impacts caused by high temperatures on urban tree species in China.

Symptom	Affected Species	Reported Cities	Reported Occurrence
Drought	88	18	18
Sunburn	90	7	7

Tree species that were frequently affected by high temperatures include maidenhair tree (*Ginkgo biloba* L.), camphor tree, southern magnolia (*Magnolia grandiflora* L.), common camellia (*Camellia japonica* L.), and dawn redwood (*Metasequoia glyptostroboides* Hu & W.C. Cheng). Both drought stress and sunburn were frequently observed on these species under high temperature.

Besides these species, Sims's azalea (*Rhododendron simsii* Planch.), white champaca (*Michelia alba* DC.), Japanese aralia (*Fatsia japonica* (Thunb.) Decne. & Planch.), and Japanese holly (*Ilex crenata* f. convexa (Makino) Rehder) were often subjected to severe sunburn. Severe drought stress symptoms were also frequently reported on species including golden privet (*Ligustrum* × *vicaryi* Rehder), purple leaf plum (*Prunus cerasifera* f. atropurpurea (Jacq.) Rehd.), and lily magnolia (*Magnolia liliiflora* Desr.) (See Supplementary Table S1 for more information).

Low temperature can cause injuries to and deaths of trees. Cities in south China reported more occurrences of low-temperature damages and more number of affected species than cities in the other two regions (Table 2). The data also showed that much lower temperatures were required to cause damages on urban trees growing in cities in north China.

Table 2. Summary of impacts caused by low temperature on urban tree species in China.

Symptom.	Affected Species	Reported Cities	Reported Occurrence
North China (reported temperature range: −37.4 °C—−20.2 °C)			
Injury	50	7	9
Death	23	2	2
Central China (reported temperature range: −23.4 °C—−2.2 °C)			
Injury	270	19	20
Death	34	9	10
South China (reported temperature range: −12.7 °C—−5.7 °C)			
Injury	586	24	30
Death	131	16	19

Species that were frequently damaged by low temperature were different in different regions. In cities in north China, they were white poplar (*Populus alba* var. pyramidalis Bunge), southern Chinese pine (*Pinus tabuliformis* Carrière), rose of Sharon (*Hibiscus syriacus* L.), and Japanese pagoda tree (*Styphnolobium japonicum* (L.) Schott). In cities in central China, camphor tree, Chinese firethorn (*Pyracantha fortuneana* (Maxim.) H.L. Li), fragrant olive (*Osmanthus fragrans* Lour.), and oleander (*Nerium indicum* Mill.) were the most frequently reported species. In cities in south China, on the top of list were Chinese hibiscus (*Hibiscus rosa-sinensis* L.), council tree (*Ficus altissima* Blume), glossy shower tree (*Cassia surattensis* Burm.f.), and fishtail palm (*Caryota ochlandra* Hance.). However, there were also overlaps. Seventeen species were both reported in cities in north and central China, and 86 species were reported in cities in central and south China. Even cities in south and north China shared a common list of 24 species. Eight species were reported in all three geographic regions. They were Chinese boxwood (*Buxus sinica* var. parvifolia M. Cheng), Japanese quince (*Chaenomeles speciosa* (Sweet) Nakai), Prickly cypress (*Juniperus formosana* Hayata), golden privet, Kaido crab apple (*Malus micromalus* Makino), white champaca, Oriental arborvitae (*Platycladus orientalis* (L.) Franco) and a cultivar of Oriental arborvitae (*Platycladus orientalis* var. sieboldii (Haw) Hu.) (See Supplementary Table S2 for more information).

3.4. Wind Impacts

Strong winds mainly caused damages on trees in inland cities such as Beijing, Taian, and Hefei while typhoons mainly impacted coastal cities such as Guangzhou, Zhanjiang, and Haikou (Figure 2). Coastal cities in southeast China were more frequently impacted by typhoons.

Wind can cause different types of mechanical damages—from damaging small twigs to uprooting of entire trees (Table 3). The most severe form of damage (i.e., uprooting) was reported more frequently by cities.

Among the 190 species damaged by wind, camphor tree, rose of India (*Lagerstroemia speciosa* (L.) Pers.), glossy shower tree, Japanese pagoda tree often had broken branches. Damages on canopies were frequently reported for Royal palm (*Oreodoxa regia* Kunth) and Jack tree (*Artocarpus heterophyllus* Lam) but they were rarely uprooted by wind. On the contrary, canopies of camphor tree, southern magnolia, and willow trees (*Salix* spp.) were frequently damaged by strong wind and they were also often uprooted. Japanese pagoda tree was also frequently reported to have broken stems and tilting trees caused by strong wind. Among all species that have been reported to be uprooted by wind, glossy shower tree was the most frequently reported species, followed by rose of India, mountain ebony (*Bauhinia variegata* L.), and Japanese pagoda tree (see Supplementary Table S3 for more information).

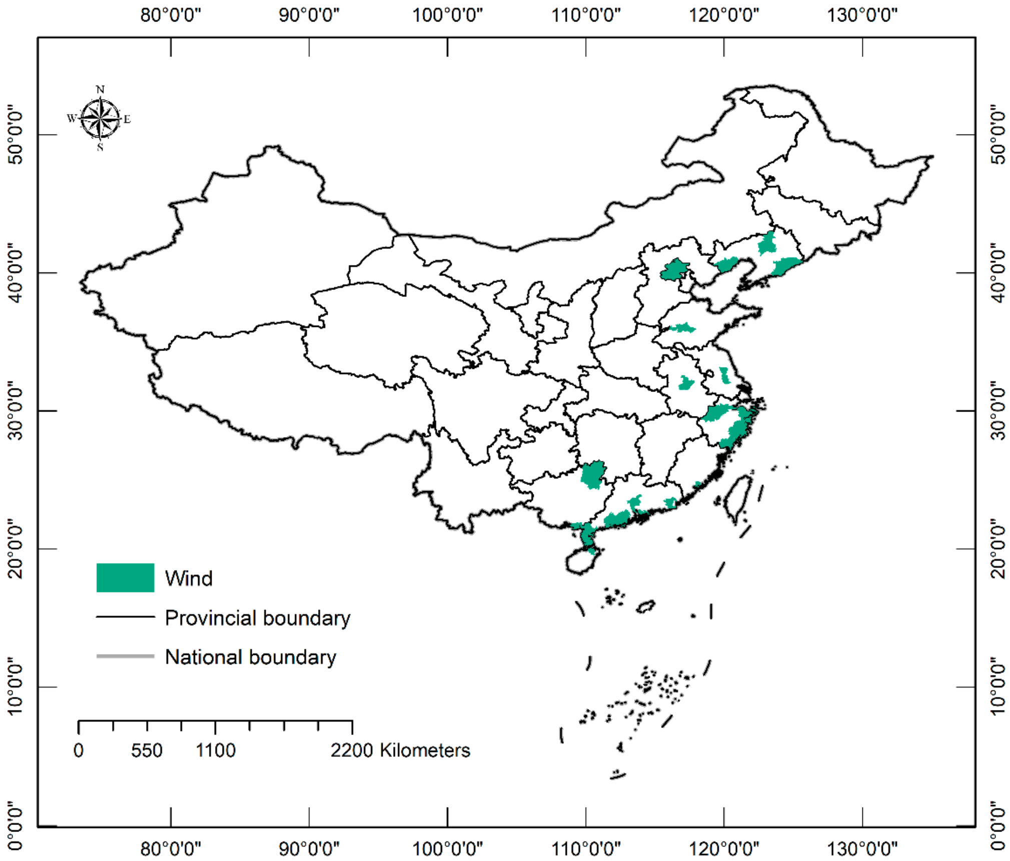

Figure 2. Spatial patterns of wind damages on urban trees in China.

Table 3. Summary of wind impacts on urban tree species in China.

Symptom	Affected Species	Reported Cities	Reported Occurrence
Broken branches	42	7	7
Canopy loss	91	8	8
Broken stems	28	8	8
Tilting	79	6	7
Uprooting	115	15	17

3.5. Impacts of Snow

Snow is the least frequently reported type of disturbance on urban trees. It mainly occurred in north and central China. The only city in south China where it was reported is Xichang. The city is located in a subtropical climate zone but has an elevation between 1500 and 2500 m (Figure 3).

The main impacts caused by snow were mechanical damages, followed by cold injuries (Table 4). Waterlogging only occurred infrequently on a couple of species.

Mechanical damages occurred more frequently on Japanese pagoda tree and Chinese willow (*Salix matsudana* Koidz.). Species such as fragrant olive, Japanese blueberry (*Elaeocarpus decipiens*

F.B.Forbes & Hemsl.), and California fan palm (*Washingtonia filifera* (Linden ex André) H.Wendl. ex de Bary) were reported to sustain cold injuries caused by snow. Waterlogging only occurred on maidenhair trees and a cultivar of tree of heaven (*Ailanthus altissima* 'Umbraculifera') (See Supplementary Table S4 for more information).

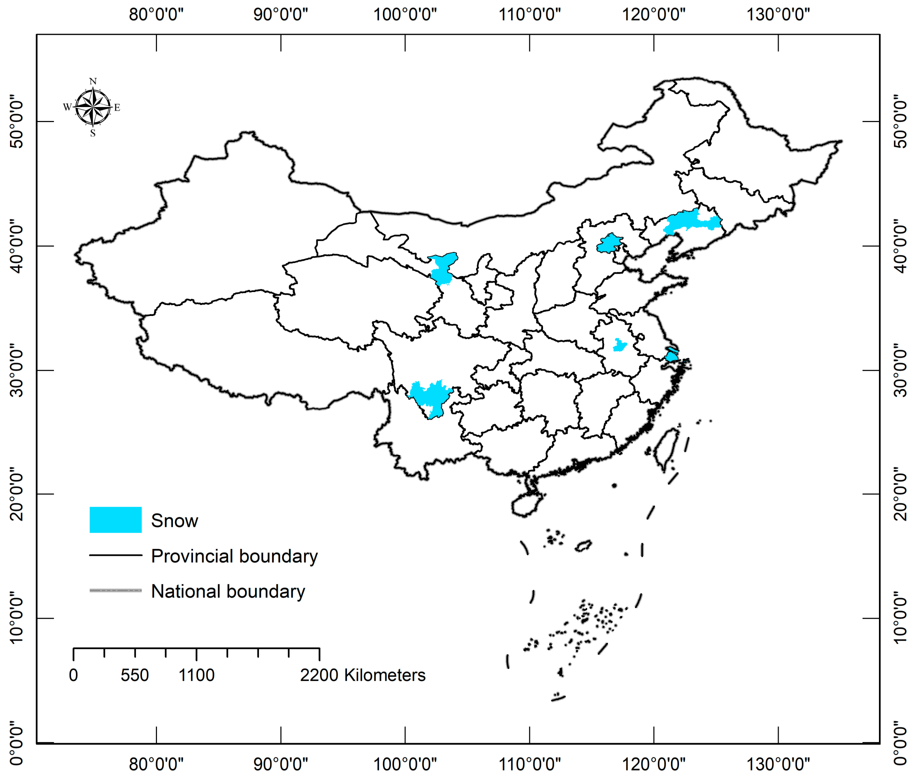

Figure 3. Spatial patterns of damages on urban trees caused by snow in China.

Table 4. Summary of impacts caused by snow on urban tree species in China.

Symptom	Affected Species	Reported Cities	Reported Occurrence
Cold injury	33	3	3
Mechanical damage	72	3	4
Waterlogging	2	4	4

3.6. Impacts Caused by Diseases and Pests

There was no clear spatial pattern of disturbances on urban trees caused by diseases and pests (Figure 4). Because most cities are located in east China, more cities in this region reported diseases and pests than those of west China.

Leaf diseases such as anthracnose and rust diseases were the dominant types of disease on urban trees (Table 5). Also, diseases such as cankers on branches and stems were frequently reported by cities (See supplementary data for more information).

Among species affected by diseases, Chinese rose (*Rosa chinensis* Jacq.), poplar trees (*Populus* spp.), willow trees, golden privet, common crape myrtle (*Lagerstroemia indica* L.), and council tree were ranked at the top for the frequency of reported leaf diseases. For branch and stem diseases, poplar trees and willow trees were the top two genera that were frequently reported to have this type of disease. They were followed by Siberian elm (*Ficus altissima* Blume) and black locust (*Robinia pseudoacacia* L.). A cultivar of Chinese juniper (*Sabina chinensis* 'Xian') was reported to have the most frequent occurrence of systemic diseases. (See Supplementary Table S5 for more information).

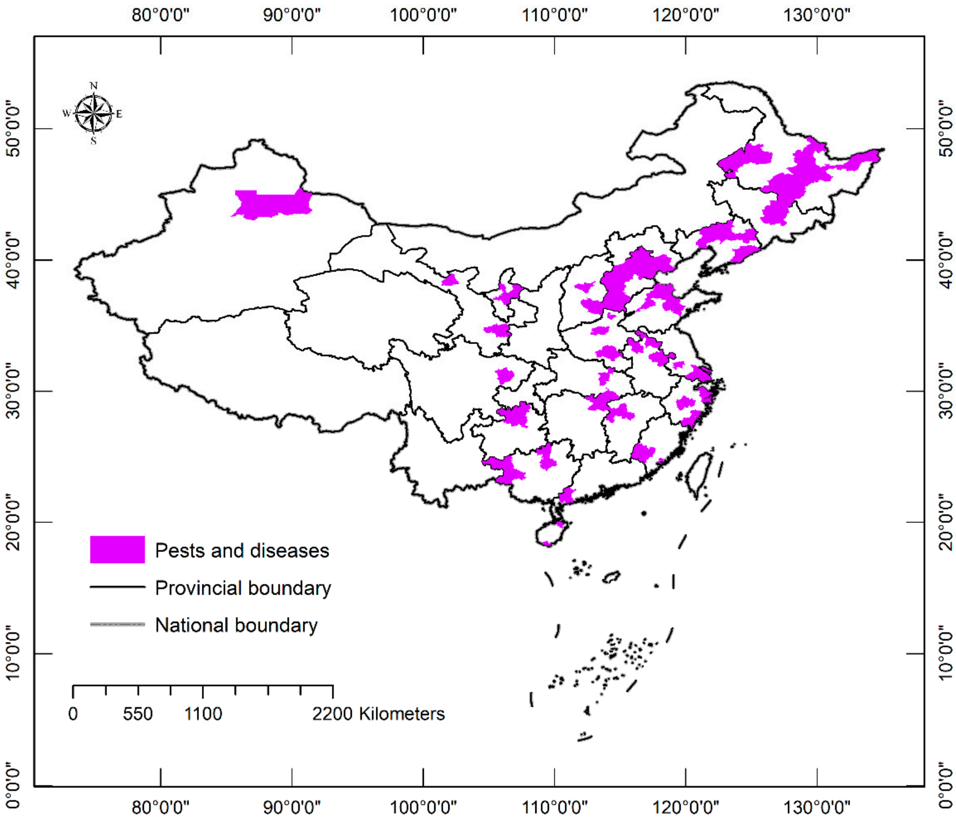

Figure 4. Spatial patterns of damages on urban trees caused by pests and diseases in China.

Table 5. Summary of impacts caused by diseases on urban tree species in China.

Type	Affected Species	Reported Cities	Reported Occurrence
Leaf disease	130	25	30
Branch/stem disease	33	19	21
Root disease	10	4	4
Systemic disease	18	11	11

Similar to diseases, pests attack leaves of urban trees more often than other organs (Table 6). Larvae of various species such as large rose sawfly (*Arge pagana* (Panzer)) and Oriental moth (*Cnidocampa flavescens* Walker), and beetles such as leaf beetle (*Ambrostoma quadriimpressum* Motschulsky) were major defoliators. Scale insects (Coccoidea) and aphids (Aphidoidea) were main sapping pests. Major pests that damaged branches included pests such as termites (Termitidae), which affected a wide range of tree species. There were also pests that only damaged branches of a few specific tree species such as red palm weevil (*Rhynchophorus ferrugineus* (Olivier)), which mainly affected coconut (*Cocos nucifera* L.) and palm trees. More information can be found from the supplementary data.

Table 6. Summary of impacts caused by pests on urban trees in China.

Types	Affected Species	Reported Cities	Reported Occurrence
Defoliator	133	23	28
Sapping pest	171	25	27
Borer	76	23	33
Underground pest	3	1	1

Among tree species, poplar trees and willow trees were again frequently reported for leaf damages caused by defoliators. Other species that were frequently attacked by defoliators included Chinese ash (*Fraxinus chinensis* Roxb.), purple leaf plum, Japanese pagoda tree, common crape myrtle, camphor tree, Siberian elm, and Chinese rose. All these tree species were also commonly infected by sapping pests. Besides them, severe infections of sapping pests were reported on tree species such as peach (*Prunus persica* (L.) Batsch), Japanese box (*Buxus megistophylla* H. Lév), Yoshino cherry (*Cerasus yedoensis* (Matsum.) T.T. Yu & C.L. Li), flowering peach (*Amygdalus persica* var. persica f. duplex), and oleander. Tree species frequently attacked by borers include willow trees, Chinese ash, Japanese pagoda tree, golden rain tree (*Koelreuteria paniculata* Laxm.), and silver maple (*Acer saccharinum* L.) (See Supplementary Table S6 for more information).

4. Discussion

4.1. Spatial Patterns of Occurrences of Disturbances on Urban Trees in China

Our results showed that there were distinctive spatial patterns of occurrences of different types of disturbances. Damages caused by high temperature mainly occurred in cities in central China. Several cities that reported damages caused by high temperature, including Nanjing, Wuhan, Changsha, and Chongqing, are known as "furnace cities" in China for their high summer temperatures [25]. For the two cities in northwest China, Baoji and Wuwei, the local climate of this region features hot and dry summers [26,27]. Urban trees planted in cities in this region are frequently exposed to the impacts of high temperature.

It is surprising to find out that damages caused by low temperature occurred more often in south China than other parts of China. Intuitively, we would expect that cold injuries would be more frequent in cities in north China. There are two possible explanations. First, cities in north China plant less number of species and most of them are acclimated to the low temperature. For example, there were only 34 tree species in the northernmost city—Heihe (50°14′42″ N, 127°28′54″ E) while the median number of tree species reported in 210 cities in China was 85 [28]. Cities in south China in general plant more species and potentially increase the pool of species sensitive to low temperature. Another possible reason is that cold injuries are common in north China, so people do not report them unless severe damages occur. Therefore, there is a bias in reporting. On the contrary, cold injuries are less common in south China so people pay attention to this disturbance when it occurs.

The patterns of disturbances caused by wind and snow largely followed our expectation. Wind damages on trees mainly happened in coastal cities. This is because extreme wind speeds are frequently observed along the coastline of China, especially in the southeast section, where typhoons occur frequently [29]. Snow damages mainly occurred in north China. However, extreme snow events—while they are rare—can occur in central and south China and cause significant damages to trees [30].

There were no distinctive patterns of occurrences of pests and diseases on urban trees in cities in China. Cities that reported damages of pests and diseases largely follow the spatial distribution of cities in China: mostly in east China and less in west China [31].

4.2. Susceptibility of Urban Tree Species to Disturbances

Among the tree species frequently damaged by high temperature, there are several categories. Species such as common camellia and Japanese aralia like partial shade [32,33]. Exposure to full sun can lead to damages and poor growth. Species such as dawn redwood like moist soil, so they can be stressed when subjected to severe droughts caused by the combination of high temperature and low water availability [34]. Species such as maidenhair tree, camphor tree, and southern magnolia can tolerate droughts and strong sun lights [35–37]. Damages caused by high temperature on these species are mainly due to the poor planting practices, e.g., compacted soil in small planting pits restricted water supply while temperature was high [38].

The main reason for cold injuries and deaths caused by low temperature is the planting of a species out of its natural distribution range. The large number of species that were injured by low temperature in south China are tropical species planted in subtropical or warm temperate climates. For example, species frequently damaged by low temperature such as Chinese hibiscus, council tree, glossy shower, and fishtail palm all originate from tropical regions. In central China, where cold damages on camphor tree were frequently reported, most of these cases occurred in cities that are outside or at the edge of the natural distribution range of camphor tree.

Tree species that are susceptible to wind damages share some common features. Many of them have dense canopy (e.g., camphor tree), brittle woods (e.g., silver maple), or shallow root systems (e.g., glossy shower tree). Species susceptible to wind damages reported in China corroborate with the susceptible species reported in the southern United States of America partially. Weeping banyan (*Ficus benjamina* L.) and silk oak (*Grevillea robusta* A.Cunn. ex R.Br.) were listed as urban tree species that have the lowest wind resistance in the southern US [39]. They were also reported to be damaged by winds severely in China. However, cities in China reported severe damages on southern magnolia. This species was listed among species that have the highest wind resistance in the southern US [39]. The discrepancy may be explained by tree planting practices in China. Large trees are often planted in small pits and the growth of their root systems has been restricted [40], which makes them easy to be tilted or uprooted by wind.

We found out that the tree species that were frequently impacted by diseases and pests were also species widely used in cities in China. According to Yan and Yang (2017), purple leaf plum was among the ten most widely distributed species in urban China. Also, the genus *Salix* was among the ten most widely distributed genera. They were both reported frequently by cities in terms of occurrences of diseases and pests. A possible explanation for our observed pattern is that more diseases and pests were reported for these species because they were more common. However, the possibility that these species are more susceptible to diseases and pests cannot be ruled out. This can be attributed to the monoculture of particular cultivars or clones of these species [41], which are often selected for fast growth and aesthetic features rather than resistances to pests and diseases. Another contributing factor is the accumulation of propagules of pathogens and pests for these species in urban environments due to their extensive use [42].

4.3. Implications of Findings

By examining the impacts of five main types of disturbances (low and high temperature, snow, wind, and pests and diseases) on urban trees across cities in China, our study added new knowledge to urban forestry. Comparing to studies that have focused on tree species in a single city, the results of our study offer better opportunity to generalize the tolerance of a particular species or cultivar to a specific type of disturbance. The large-scale synthesis helped to identify susceptible species from thousands of urban tree species. Further evaluations can be conducted on these species using more complex methods [43].

Our findings provide useful information for cities in China to select suitable species for urban greening. First, cities in different regions should pay attention to different types of disturbances. For cities in north China, the tolerance of the species to low temperature, snow, and wind should be considered when selecting tree species. For cities in central China, particular attention should be paid to the tolerance of species to low and high temperatures and snow. For cities in south China, they need to look at the tolerance of species to low temperature and wind. To pay special attention to the tolerance of low temperature in south China may sound counterintuitive. However, the large number of species and cultivars (586 taxa) reported to sustain cold injuries shows that this issue needs urgent attention in this region, especially when some species and cultivars developed cold injury symptoms under above-zero temperatures. Attention to wind resistance of trees is important for coastal cities. All cities need to pay attention to species that are infected by multiple diseases and pests. Besides, tree species should be selected by examining their performances to different types of disturbance comprehensively. Our results showed that some widely planted tree species, such as poplars and willows, were often reported to have broken branches in strong wind. They were also infected by pests and diseases frequently. To reduce safety risks posed by broken tree branches and the exposure of residents to chemicals used for controlling pests and diseases, the use of these species should be reduced or avoided in places where population density is high.

Furthermore, based on our findings, cities can take maintenance measures to reduce the damages of disturbances on susceptible species. For example, to reduce drought stress caused by high temperature, irrigation should be provided for susceptible species. To avoid sunburn, sensitive species should be avoided in places exposed to full sun. In cities where the wind hazard is severe, species that have brittle woods or shallow root systems should be avoided in places where pedestrians or properties can be at risk. At the same time, management measures such as canopy reduction can help to reduce wind damages. Finally, cities should reduce the use of species that are susceptible to multiple disturbances, e.g., poplar trees and willow trees, which can often increase maintenance costs.

4.4. Limitations of the Current Study

While our findings provide useful information for understanding the performance of urban tree species under major categories of disturbances in China, the limitations of our study should be kept in mind when interpreting our results. We only had occurrence records of damages caused by various disturbances on species in 120 cities. We lacked detailed information on the age, size, quantity, and site condition of these trees as well as maintenance practices that have been applied to them. These factors added uncertainties to our findings. Earlier we showed an example of a tree species classified as resistant to hurricanes in the US but subject to severe damage from typhoons in China due to poor planting practices. A limitation of our study is that we only included published materials in the analysis. Although information contained in published materials is more reliable because they went through various forms of peer reviews, unpublished materials such as internal work reports from urban forest management agencies may also contain valuable information on performances of urban tree species. It will be desirable to find ways to work with these agencies to explore the use of these unpublished materials.

Ideally, the performance of tree species under different types of disturbances should be evaluated with well-controlled experiments. However, to conduct controlled studies on thousands of tree species growing in cities is not realistic. Therefore, field observations of the performance of urban trees affected by disturbances are an acceptable way to provide a coarse assessment of performances of urban tree species under these disturbances.

5. Conclusions

To increase species diversity of urban forests requires the use of more tree species. However, urban trees frequently face the challenges of different types of disturbances. There is an urgent need to evaluate the performance of tree species under different disturbances to inform practitioners when selecting species for urban greening. This need is especially strong in China as urban greening in China is going at an unprecedented speed during the rapid urbanization.

In this study, with the most comprehensive data set on the impacts of five major types of disturbances on urban trees in China, we revealed the spatial pattern of occurrences of these disturbances, and the performances of urban tree species impacted by these disturbances. We identified 1010 taxa of trees in 120 cities that have been affected by these disturbances. The information is vital for cities in China to select the right tree species in their urban greening projects. At the same time, because many species studied in this study are also widely planted in cities in other countries, our findings can provide useful guidance to urban greening in cities in other countries too. In the future, it will be desirable to expand the study from China to include more countries, which will allow for better generalization of the tolerance of urban tree species to different types of disturbances.

Supplementary Materials: The following materials are available online at http://www.mdpi.com/1999-4907/9/2/50/s1, Table S1: Tree species affected by high temperature and the level of severity of damage, Table S2: Tree species affected by low temperature and the level of severity of damage, Table S3: Tree species affected by wind and the level of severity of damage, Table S4: Tree species affected by snow and the level of severity of damage, Table S5: Tree species affected by diseases and the level of severity of damage, Table S6: Tree species affected by pests and the level of severity of damage, and the data used in this study.

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