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ORIGINAL RESEARCH ARTICLE

A study of climate resilience in urban tree species of Peninsular Malaysia

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ABSTRACT

Climate change poses significant challenges to Malaysian cities, including heat stress, which high humidity and the urban heat island effect exacerbate. While trees effectively reduce temperatures and improve microclimates, potential sensitivities to climate change impacts require careful species selection. Experts assessed the resilience of 220 tree species from urban and rural areas of Malaysia using eight criteria, based on a list compiled from four sources. We then categorised the species by sensitivity for four urban landscape types. Saltwater sensitivity had the highest proportion of sensitive species, followed by inundation sensitivity. Considering regional climate projections, planners should prioritise species with low inundation sensitivity. Data availability for saltwater, inundation, and high-temperature sensitivities was limited but adequate for the remaining criteria, with susceptibility to predation, parasitism, or disease, and sensitivity to storm conditions being of concern. Urban planners should integrate these criteria into decision-making to ensure climate-smart urban design. Given that our knowledge about the effects of climate change on tree species will advance and should be documented, we developed an open-collaborative online database that assists stakeholders in selecting suitable species for various sites in Malaysia. Moderators will review submissions to ensure consistent application of criteria and alignment between selected answers and supporting information. Assessors can contribute to quality control by voting for assessments they agree with. Our research emphasises the importance of proactively addressing climate change challenges in urban areas and underscores the value of informed decision-making to enhance the resilience of urban tree populations.

Keywords: climate adaptation; climate vulnerability; species selection; trait-based approach; tree database; urban forest

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1. Introduction

Urban areas in Malaysia will be exposed to extreme heat in the coming decades due to climate change and the urban heat island (UHI) effect. The global number of heatwave days is increasing twice as fast in cities than in rural or natural surroundings[1]. The cumulative effect of climate change and the UHI will likely have a significant impact on public health[2–4], with consequences such as reduced work capacity and labour productivity in vulnerable populations[5,6]. It may also severely compromise outdoor activities. Besides temperature, humidity severely limits the ability of the human body to thermoregulate[6]. Recent findings have shown that humid heat is even more threatening to human life than previously thought[7]. This will likely become a significant challenge in Malaysia, a country already experiencing urban temperatures above human comfort levels, and where air conditioners alone account for 53% of electricity consumption in Malaysian buildings[8]. For comparison, households in the USA spend an average of 12% on air conditioning[9].

Urban greening, defined as efforts to enhance green spaces within cities, encompasses activities aimed at modifying and maintaining the qualities and extent of urban vegetation[10], can significantly reduce urban temperatures, the UHI effect[11] and energy consumption[12], and can improve microclimatic conditions[11]. In addition, the benefits provided by tree canopies cause minimal interference at the ground level. Compared to other green spaces, street trees provide more benefits[13] and are easily integrated into existing streets. They also have a significant impact on public health, and studies have shown that it may be more beneficial to plant trees on streets than in parks for that purpose alone[13].

The Nature-based Climate Adaptation Programme for the Urban Areas of Penang Island, the first urban climate adaptation programme developed for the country[14], prioritises the strategic planting of trees and green spaces to reduce temperatures. **Figures 1** and **2** verify the beneficial impacts of this approach by demonstrating stark differences in surface temperature between shaded and non-shaded areas of George Town, Penang. **Figure 1** illustrates that tree-lined streets are easily identifiable due to their lower surface temperatures and linear nature. **Figure 2** highlights a difference of 28.8 °C in maximum surface temperature between Jalan Brown (9.58 a.m.), a tree-lined road, and Lebuh Gereja (10.59 a.m.), a street within the UNESCO World Heritage Site.

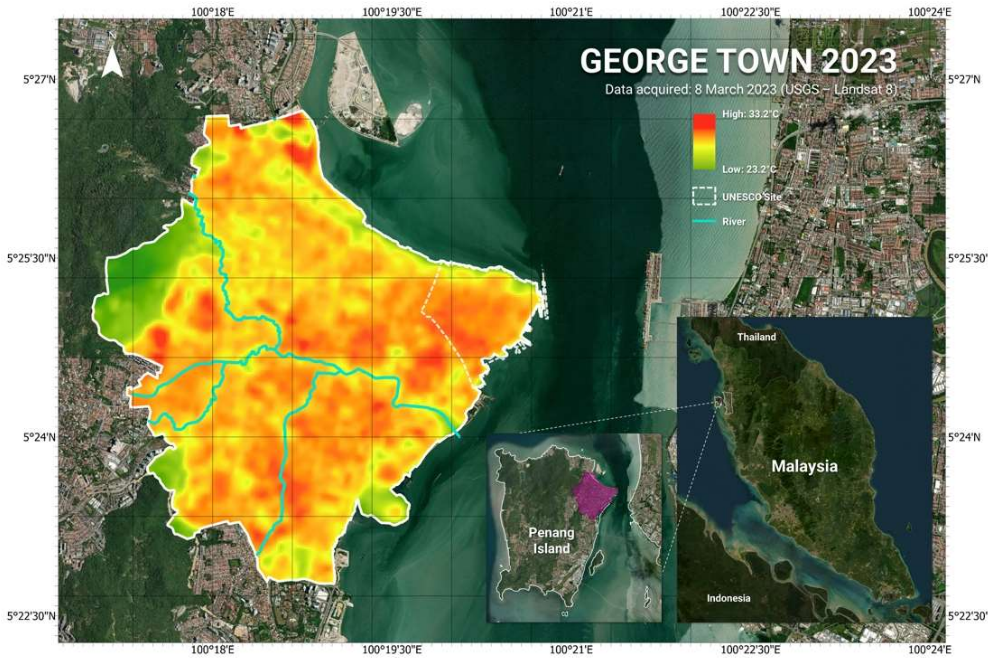

Figure 1. Land surface temperature of George Town, Penang in 2023 (Produced with Landsat-8 data courtesy of the U.S. Geological Survey).

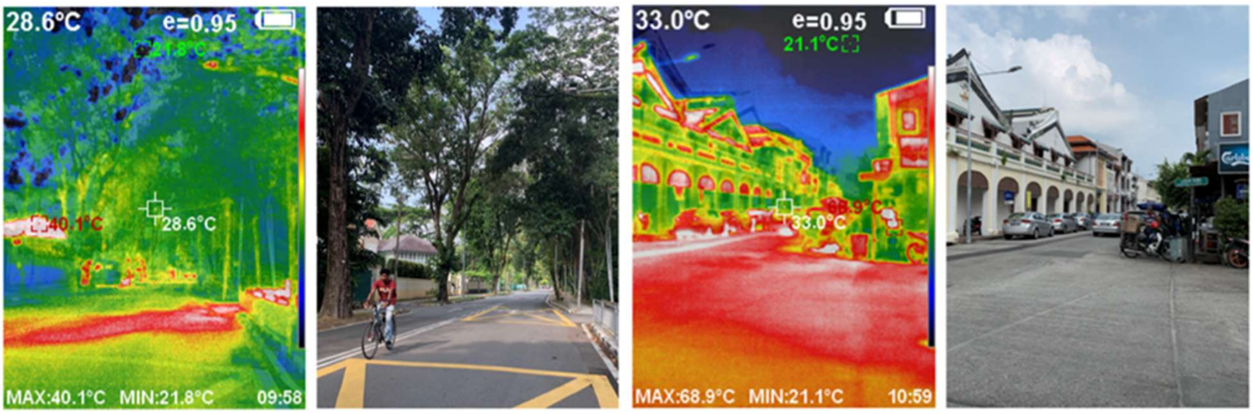

Figure 2. Thermal images taken in George Town, Penang (12 July 2019) (Produced with a Perfect Prime IR0006 Thermal Imager Camera).

Malaysia is one of the most biodiverse countries in the world, ranking twelfth on the National Biodiversity Index, which is based on estimates of species richness and endemism of four terrestrial vertebrate classes and vascular plants[15]. An estimated 5,200 tree flora occur in Malaysia[16]. Of this, around 2830[17] and 4000 occur in Peninsular and East Malaysia, respectively, with an overlap of 1559 or 30%[16].

When selecting species to improve urban climate conditions, the impacts of climate change on candidate species should be considered. Several studies have addressed the need to understand the resilience of urban tree species to climate change impacts. One in California scored 73 species on habitat suitability, physiology and biological interactions and then planted and evaluated 144 specimens in experimental plots[18]. Another in Shanghai[19] focused on 65 urban tree species and developed an adaptability assessment framework for the impacts of climate change. A third[20] subjected 20 Australasian tree and shrub species to heat and drought stresses and found that water loss at high temperatures can drive species towards mortality thresholds faster than expected. Different methodologies are adopted according to the goals of each study, which vary with the specific region and climate under consideration.

This study is intended as a first step towards understanding tree species' resilience to climate-related stresses in urban settings in Malaysia. It aims to identify species that will be more likely to withstand changes in the urban climate of Malaysia in the coming decades, which will help inform climate-smart urban planning.

2. Materials and methods

2.1. Selection of species for assessment

All species considered in this assessment are trees, shrubs, and palms found in urban and rural areas in Malaysia, based on a list compiled from four independent sources. The main source was the Malaysian National Landscape Department, which has published guidelines for city councils on selecting tree species for public parks and avenue landscaping[21]. The guidelines, which were developed based on an extensive review of government documentation, mention that rising urban temperatures and high surface water runoff rates require consideration when selecting plant species.

The other three sources were MLA Landscape Architects, an award-winning landscape architecture firm with nearly 40 years of experience; ISA Certified Arborist (CA) Gunasilan Ramasamy, an expert arborist; and Dato' Dr. Saw Leng Guan FASc, an expert botanist and former Curator of the Penang Botanic Gardens and Director of the Forest Biodiversity Division at the Forest Research Institute of Malaysia. It is common practice for professional arborists and botanists, with knowledge of local tree species, to curate and maintain urban tree lists[22]. These three sources provided unpublished lists of species that occur in Malaysian cities. The original list provided by Dr Saw, for example, was based on an extensive review of literature on tropical gardening and tree listings used in landscape plantings and streets, the most notable being The Wayside Trees of Malaya[23]. The original lists of Dr Saw, CA Gunasilan, and MLA were then reduced to fit the context of the study, based on the characteristics, functions, and uses of the species and their availability in nurseries.

These four lists were combined into a single list, duplicate species removed, and the taxonomic nomenclature checked using the International Plant Name Index, as well as other sources including the IUCN Red List of Threatened Species[24], the Malaysia Biodiversity Information System (an online repository for biodiversity information in Malaysia)[25], and Malaysia Red List: Plants of Peninsular Malaysia, Volume 1[26]. Following the above processes, we retained 251 species for assessment, although data for 31 species were considered insufficient to warrant inclusion, so our final assessment contained 220 species. Although this number is relatively small compared to the number of tree species in the country, it is representative considering that an average of 92 tree species are planted in cities[22].

2.2. Landscape suitability classification

The four landscape types identified for this study were urban streets, small urban green spaces, blue-green corridors, and coastal fronts, of which each presents different challenges for tree species selection. On urban streets, trees face the most significant challenges. In addition to pollution and exposure to the UHI effect, there is very little space for the root system to develop. The tree pits are relatively small, and the surrounding soil is usually compacted[27]. Therefore, species in these areas must be slow growing to allow the root system to keep up with the growth rate of the canopy; otherwise, they are at risk of uprooting during storms. In small urban green spaces, trees also face pollution and the UHI effect but typically have more room for root development. Consequently, tree species with faster growth rates can also be considered. In blue-green corridors, all species must be riparian or have a high tolerance to waterlogging[28]. At coastal fronts, defined as all areas within 400 m of the coast, trees will be exposed to salt sprays and must therefore tolerate saltwater[29].

2.3. Protocol for assessing resilience to climate change

The protocol used in this study to assess species resilience to climate change was broadly based on the methods applied by Lee et al.[30], which were based on the concepts first applied by Foden et al.[31]. Foden and colleagues developed and applied a framework that considered three broad dimensions of vulnerability to climate change: (1) 'exposure' (the extent and nature of the anticipated climatic changes that a species is expected to experience); (2) 'sensitivity' (the ability of a species to persist in situ despite climate change); and (3) 'adaptive capacity' (the ability of a species to persist through dispersal and/or microevolutionary change). Each dimension contains several criteria and associated assessment criteria that can be systematically considered for each species to determine its vulnerability to climate change.

This framework has since been adapted and applied to a broad range of taxa and at various geographical levels (e.g., see Carr et al.[32] or Tognelli et al.[33]). In their 2019 publication, Lee et al.[30] adapted this framework to instead gauge levels of species resilience and applied this to a range of plants from Kutai National Park, Indonesia. The aim was to identify species that are suitable for reforestation efforts and can withstand future climates, and their assessment revealed that species that are most likely to be climate change resilient were dominated by pioneer or invasive species. Such 'trait-based' assessments are ideal for studies such as our own, as they allow assessment of large numbers of species in the absence of robust species distribution data while providing insights into the specific mechanism(s) of potential impact (e.g., mortality from flooding, increased disease prevalence), allowing targeted pre-emptive actions to be taken[34,35].

The criteria used to assess the resilience or vulnerability of plant species to climate change were developed through consultation with plant experts from the IUCN's Species Survival Commission, including Plant Specialist Group Chairs and Stand-alone Red List Authority Coordinators, who coordinated the feedback from their wider membership. These experts identified 63 potential criteria for assessing climate change resilience or vulnerability through criteria of sensitivity and adaptive capacity. In this study, we first considered all 63 of these plant vulnerability criteria for applicability in the context of our work and, following discussions between collaborators (co-authors and selected external experts), excluded 55, leaving a final list of eight. The criteria that were excluded from this work (and justifications for doing so) include the following: all criteria related to the ability of a species to adapt through migration and/or across successive generations, since, in the context of urban environments, it is not desirable that species move or naturally regenerate; criteria related to highly specialised lifestyles (e.g., carnivorous or epiphytic species), as such species are unlikely to be selected as candidate species (often because they relate to plant types other than trees); and criteria concerning specific factors related to climate that are irrelevant to urban environments (e.g., sensitivity to altered fire regimes). The final list of criteria used in this study is in **Table 1**. Of these, all but one (specialised habitat requirements) can be directly linked to a specific climatic factor. However, habitat specialisation in a broad context is still relevant to climate sensitivity or resilience, particularly as it may help identify aspects of vulnerability not covered by the other criteria. Therefore, we have included it in our work.

Table 1. Criteria used to assess the sensitivity of tree species to climate change.

Category	Criteria	Climate change aspect	All landscape types apply
Habitat specialisation	Species has specialised habitat requirements	Mixed	Yes
Habitat specialisation	Species is not known to occur or survive in habitats prone to saltwater intrusion	Sea-level rise	No[a]
Narrow environmental tolerances	Species is not known to occur or survive at locations that experience high temperatures (e.g., those exceeding the Malaysian mean)	Increased mean temperature and/or extreme heat conditions	Yes
Narrow environmental tolerances	Species is highly sensitive to inundation (can only tolerate <1 month)	Increased flood severity and/or frequency	Yes
Narrow environmental tolerances	Species is highly sensitive to water absence (can only tolerate <1 month)	Dry spells and droughts	Yes
Narrow environmental tolerances	Species is sensitive to storm conditions (e.g., strong wind impacts on softwood species)	Storms and strong winds	Yes
Narrow environmental tolerances	Species has specific humidity requirements	Changes in local humidity	Yes
Emerging negative interspecific interactions	Species is highly prone to predation, parasitism, and/or disease	Novel negative interactions	Yes

Note: Species were assessed as sensitive to the criteria they met.
[a]Only applies to coastal fronts.

2.4. Data collection and processing

The collation of data pertaining to the criteria in **Table 1** can be limited by a lack of sufficiently detailed, published information for many species. To overcome this, we compiled information based on experts' knowledge, which has been gained through their observations and experiences, which is recognised as a reputable means through which to estimate species' demographic and life history parameters in the absence of empirical data[34]. Following Foden et al.[31], in our context 'expert knowledge' can include any of the following: published evidence (from primary or grey literature); direct observation (e.g., of a species experiencing a weather event, such as a flood); or inferences based on observations from ecologically similar species or known ecological factors (e.g., geographical range or habitat associations of a species).

A further challenge in assessments of this nature arises from a generally poor understanding of meaningful thresholds that can be used to infer resilience or vulnerability in a real-world context[36]. As such, although most of the criteria in **Table 1** can theoretically be quantified on continuous scales, we chose to apply binary (i.e., 'Yes' or 'No') classification schemes to indicate whether individuals of a given species would be expected to survive if exposed to changes in each of the climatic factors considered. In some cases, the binary classifications used thresholds to guide assessors (e.g., species is tolerant or intolerant of inundation for >1 month), but in other cases (e.g., to assess species' tolerance to storm conditions), assigning such a threshold is challenging, and so assessors were asked to use their best judgement.

While we acknowledge that alternative approaches exist (e.g., fuzzy logic (see Jones and Cheung[37])), these typically require more detailed information and finer gradations of trait measurements, which were not available for many of our focal species and would have limited the number of species included in the analysis. They can also be difficult to interpret and communicate to non-specialists, including policymakers and practitioners, who we hope will use our findings to inform on-the-ground actions. In contrast, our approach allowed assessment of a wide range of species that do not typically have detailed supporting data. Importantly, assessments will remain of utility to end users, who will be required to consider species in the context of future climate projections for specific sites, which are also likely to have associated uncertainties. To ensure consistency between assessments and assessors, we engaged in a follow-up consultation process and anticipate that individual assessments will be further validated through additional contributions to our online database (see Section 2.5).

For the first stage of data collection, the project team compiled information based on reviews of relevant literature. An expert consultation process followed this and included a two-day workshop with eleven local experts in arboriculture, botany, and horticulture. Experts were provided with a spreadsheet of all data collected up to that point and asked to validate the information and complete the missing elements for the species that they were familiar with. In all cases, the assessors were asked to provide supporting comments to justify their choices for each aspect of the assessment. Supporting comments were generally in the form of quotations and references from published evidence, as well as descriptions of observations or experiences. Online follow-ups, typically lasting from four to eight hours (depending on the number of species the assessor evaluated), were conducted with individual assessors to verify each of their answers, and in groups to seek consensus in cases where two or more assessors provided conflicting information. Where consensus was unable to be reached or data were lacking, the criteria were assessed as 'Unknown'. The overall data collection stage lasted approximately six months.

In the results section, we present a synthesis of our findings by highlighting (a) the frequency of species possessing a given number of criteria; (b) those species assessed as sensitive under the most and least numbers of criteria; (c) the frequency of occurrence (within our dataset) of each of the eight criteria; and (d) a breakdown of our results for the four landscape types. In the case of (a) and (b), above, readers should remain aware that although a higher or lower number of criteria is broadly indicative of lower or higher resilience to change, respectively, this is very much dependent on the specific changes expected to occur at a specific site. For example, a species considered sensitive to inundation but resilient to all other changes can still be considered sensitive if the planting site is expected to experience increased flooding in the future. As such, while the combined findings presented in the main body of this paper will likely be of interest and utility to those working in climate change, urban planning, and other related fields, the greatest utility can be gained by considering our data on a species-by-species basis. Accordingly, we direct readers to our online database (see Section 2.5), which includes a summary of our full dataset. By querying this dataset, planners can consider potential tree species for planting in various contexts and locations. For example, a specific situation may arise in which the species required for planting must be highly tolerant of increased temperatures but for which flooding is less of a concern (e.g., if local climate projections suggest such conditions will occur in the future). In such a case, and indeed with other scenarios, our dataset can provide a list of candidate species for use.

2.5. Online database of climate-resilient tree species

Although Peninsular Malaysia has approximately 2830 tree flora[17], only a small selection is planted in urban spaces. The species occurrence matrix in the Global Urban Tree Inventory recorded the presence of 60 and 71 tree species in urban areas of Kuala Lumpur and Putrajaya, Malaysia, respectively[22].

When conducting this study, we found that data on many Malaysian trees, including those of relevance to climate change resilience and vulnerability, are incomplete or disconnected and often only stored in the minds of practitioners or collated by individuals in unpublished datasets. While this study helps fill this gap by consolidating data relevant to climate change, it is limited in that it only covers 220 (around 8%) of the tree flora in Peninsular Malaysia, and a better representation of Malaysian tree taxa is desirable, especially given the country's high biodiversity and contribution to global tree diversity.

Here we introduce the Atlas of Climate Resilient Tree Species (ACResT), a compilation of planting suitability-related data for tree species found in Malaysia and soon Singapore and Indonesian Borneo[38]. This online database provides practical and comprehensive utility for tree species selection, including a feature that links tree species to the nurseries in which they are available. It also provides a platform to document the characteristics (including those relating to climate change resilience) of additional tree species in the country. ACResT is a natural extension of this study, given the diversity of species in Malaysia, anticipated changes in weather patterns, and digital transformation.

The assessments for the 220 species in this study will be published on the online database and, therefore, open to review by a broader group of practitioners, helping to ensure that the criteria were applied consistently. Through this process, we hope to capture additional knowledge on the 'Unknown' elements of our assessments. The categories featured in the online database also extend to include urban suitability, biodiversity, and cultural and economic value.

The species evaluations featured on the site follow the criteria developed for this study, and individual assessments of a single species are aggregated to make them more robust and to provide a comprehensive overview of each species' traits. The composite assessments are automatically updated as new assessments are added. Like this study, the online database does not display individual assessments unless only one assessment has been made. Assessors can also add new species, subspecies, or varieties. Moderators will vet assessors and review the submissions to ensure that the criteria are applied consistently and that the supporting information provided aligns with the binary answer selected. For example, if an assessor answers that a species cannot tolerate flooding, but the supporting evidence indicates otherwise, a moderator will contact them. Quality control will also be implemented through a feature allowing assessors to vote for assessments they agree with. By developing a curated dataset on 29 criteria, the online database will help reduce shortcomings in Malaysian and global biodiversity resources. An international audience could benefit by using the information on tree species native to Malaysia but planted elsewhere as ornamentals to understand their tolerances.

Which Plant Where[39] and Right Trees for a Changing Climate[40] are both online databases developed for a similar purpose and consider flora in Australia and Great Britain, respectively. While both also assist users in determining suitable species to plant in urban areas under future climate regimes, ACResT differs from these not only in its focal location but also in its ongoing documentation of climate impacts and open-collaborative approach to addressing gaps in species knowledge.

The fixed dataset used for this research has been archived on FigShare[41] to ensure its long-term availability. As ACResT is a dynamic service with ongoing validation and data entry, users are recommended to access updated species assessments published on it. These are date-stamped and openly accessible.

3. Results and discussion

We assessed the climate sensitivity of 220 tree species commonly encountered in urban areas of Peninsular Malaysia using eight criteria and used these to derive an overall assessment for each species. **Figures 3** and **4** provide illustrative examples of species that were assessed as having high and low sensitivity to climate change, respectively. In the following paragraphs, we provide a summary of our full dataset, present results by each of the four landscape types considered, and describe the key knowledge gaps encountered in our assessments.

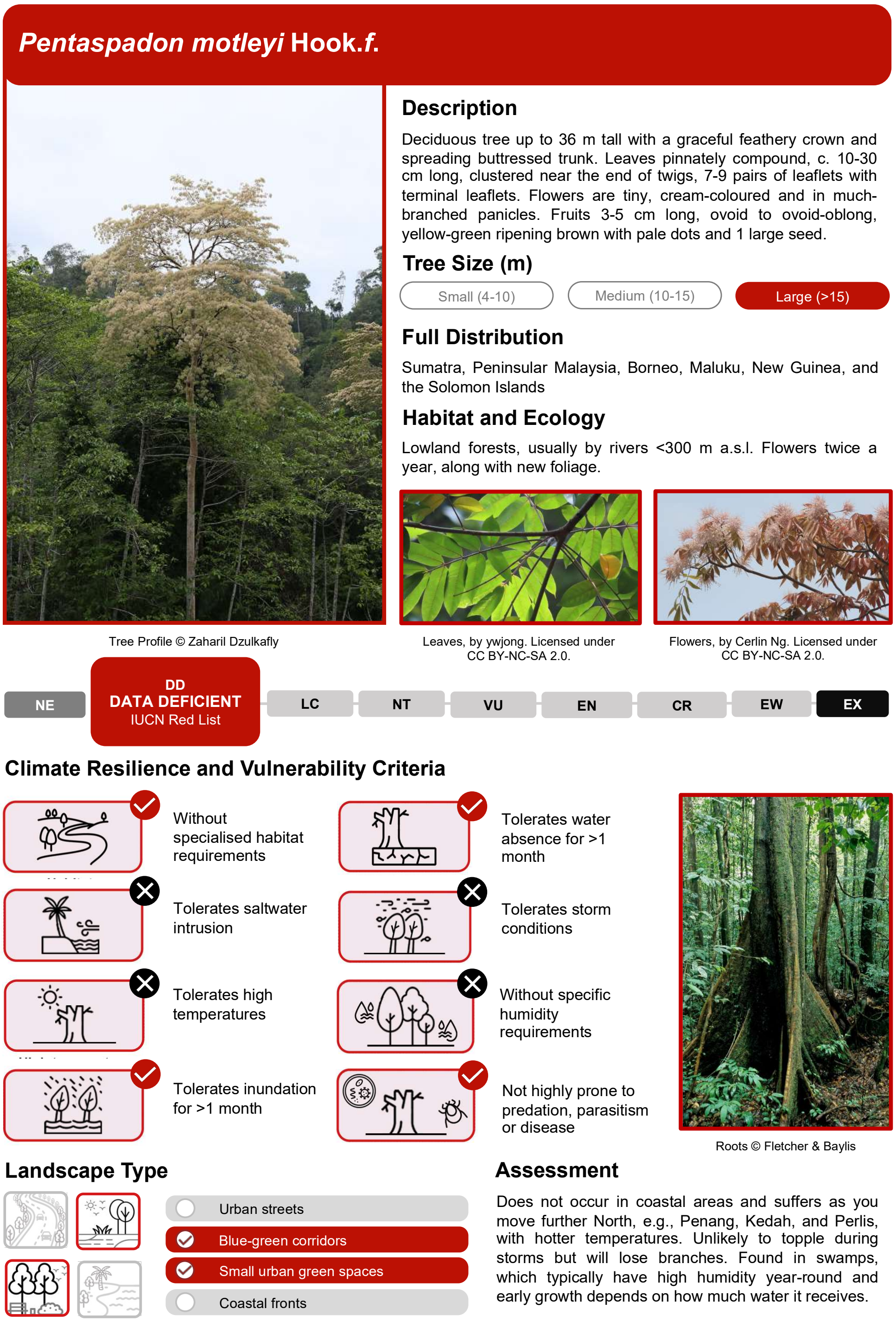

Figure 3. Pentaspadon motleyi Hook.f. was assessed as having high sensitivity to climate change. The species qualified as 'high' on four of the climate resilience/vulnerability criteria.

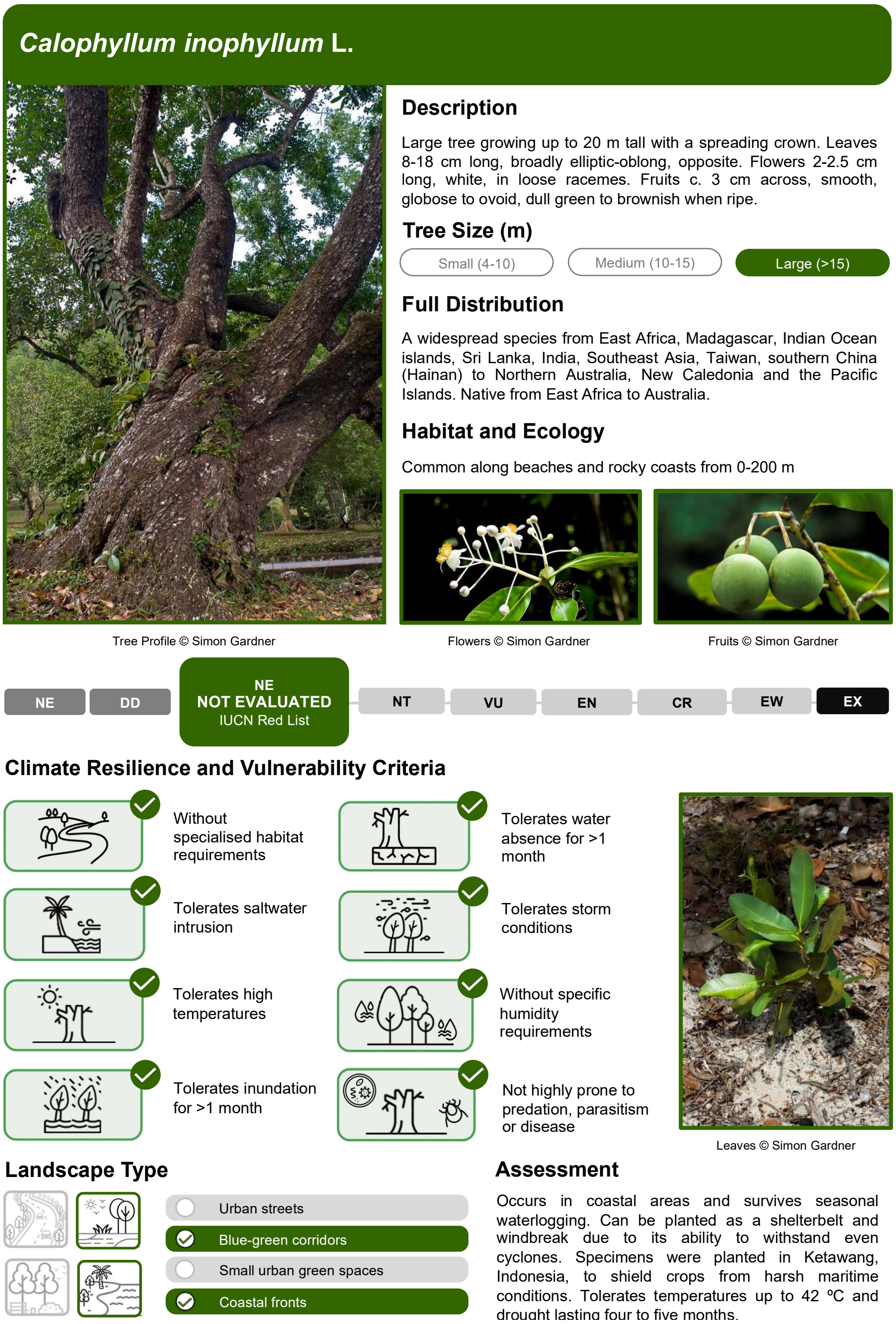

Figure 4. *Calophyllum inophyllum* L. was assessed as having low sensitivity to climate change. The species qualified as 'low' on all eight of the climate resilience/vulnerability criteria.

3.1. Summary of the dataset

The ten species that possess four or five criteria, which can broadly be considered the most sensitive among those assessed, are listed in **Table 2**. A total of 11 species qualifying as 'low' on all criteria are listed in **Table 3**. These species may be considered the most resilient of all those considered in our study.

Table 2. Species most sensitive to climate change (those with four or five sensitivity criteria) and the landscape types for which they are best suited.

Species	Urban streets	Blue-green corridors	Small urban green spaces	Coastal fronts
Pentaspadon motleyi Hook.*f.*		✓	✓	
Cananga odorata (Lam.) Hook.*f.* & Thomson		✓	✓	
Alstonia angustiloba Miq.		✓		
Alstonia spatulata Blume		✓		
Tabernaemontana corymbosa Roxb. *ex* Wall.		✓	✓	
Tabernaemontana divaricata (L.) R.Br. *ex* Roem. & Schult.		✓	✓	
Tabebuia aurea (Silva Manso) Benth. & Hook.*f.* *ex* S. Moore	✓			✓
Bucida molinetii (M. Gómez) Alwan & Stace	✓		✓	
Sesbania grandiflora (L.) Pers.		✓	✓	
Podocarpus neriifolius D. Don	✓	✓	✓	✓

Note: Only *Alstonia angustiloba* has five sensitivity criteria.

Table 3. Species least sensitive to climate change (those with zero sensitivity criteria) and the landscape types for which they are best suited.

Species	Urban streets	Blue-green corridors	Small urban green spaces	Coastal fronts
Cerbera manghas L.		✓		✓
Borassus flabellifer L.		✓		✓
Licuala spinosa Wurmb		✓	✓	✓
Livistona chinensis (Jacq.) R.Br. *ex* Mart.	✓	✓		✓
Livistona saribus (Lour.) Merr. *ex* A. Chev.	✓	✓		
Calophyllum inophyllum L.		✓		✓
Terminalia catappa L.		✓		✓
Pongamia pinnata (L.) Pierre var. *pinnata*		✓	✓	✓
Hibiscus tiliaceus L. (syn. *Talipariti tiliaceum* (L.) Fryxell)	✓	✓		✓
Syzygium grande (Wight) Walp.		✓		✓
Guettarda speciosa L.		✓	✓	✓

Figure 5 shows how our findings differ between the eight criteria used to assess sensitivity or resilience in this study. From this chart, we can see that sensitivity to saltwater and sensitivity to inundation are the two most frequently occurring sensitivity criteria encountered in our assessments, present in 63 and 59 species (or 28.6% and 26.8% of all species assessed), respectively. Each criterion was associated with a question, and the answers provided by the experts determined the sensitivity. As discussed further in Section 3.4, findings relating to the sensitivity of inundation may be of particular concern in a Malaysian context, given the projections of future flooding regimes for the country. It is also of note that these two criteria, along with sensitivity to extreme high temperatures, are those with the highest levels of uncertainty, which is discussed further in Section 3.3.

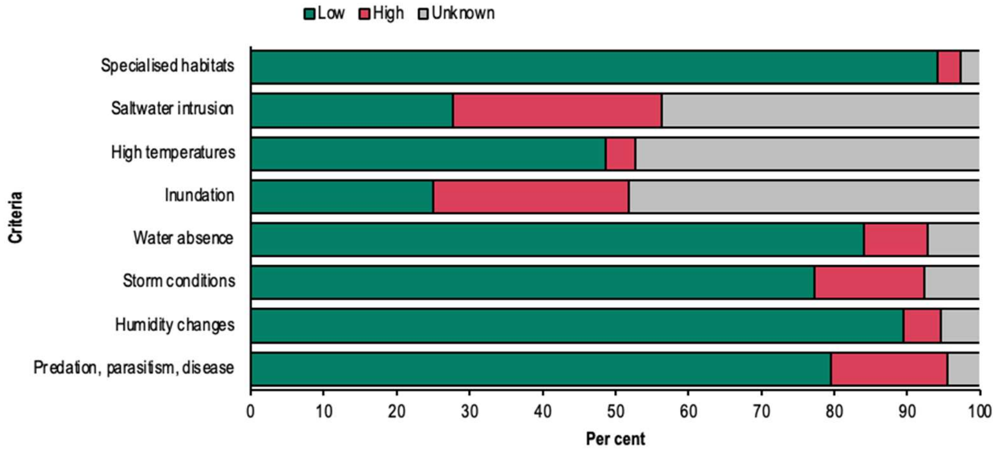

Figure 5. Percentages of all species assessed (n = 220) qualifying as having low, high, or unknown sensitivity to each climate resilience/vulnerability criterion.

Data for the remaining five criteria not mentioned above were relatively abundant. Among these, the two areas of greatest concern are susceptibility to predation, parasitism, or disease and sensitivity to storms, which were assessed as being of concern for 35 and 33 species (or 15.9% and 15.0% of the total assessed), respectively. The remaining criteria appear to be of relatively less concern, at least among the species considered in our assessment, but we note here again that the relevance of a given criterion depends on the context of the area in which planting is being considered (and especially the projected future climate conditions specific to that area), and so these less frequently occurring criteria should still be borne in mind by planners.

3.2. Results by landscape type

Figure 6 and **Table 4** show our results disaggregated by the four landscape types considered in this work. In **Figure 6**, species with 0 sensitivity criteria were considered least sensitive to climate change, and species with 4 or 5 sensitivity criteria were considered most sensitive to climate change. Only one species, *Alstonia angustiloba*, has five sensitivity criteria, representing 0.6% of the total species assessed. **Figure 6** and **Table 4** indicate that the relative proportions of the total number of criteria assigned to species and the relative proportions of species with specific criteria show little variation between landscape types, although species deemed suitable for blue-green corridors appear to have a proportionally lower number of sensitivity criteria than for other landscape types, followed by coastal fronts. However, it remains unclear whether this is a result of our sampling strategy or a finding that would apply more widely had additional species been included.

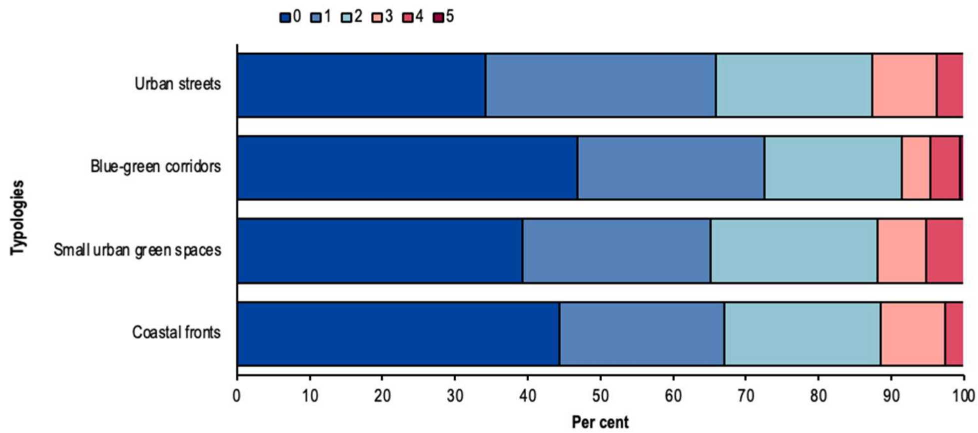

Figure 6. Percentages of all species assessed (n = 220) by the number of assigned sensitivity criteria (0–5) for each landscape type.

Table 4. Species assessed as possessing the indicated sensitivity criteria, as a number and percentage, for each landscape type.

		Sensitive to							
Landscape type	**Species allocated**	**Specialised habitats**	**Saltwater intrusion**	**High temps.**	**Inundation**	**Water absence**	**Storm conditions**	**Humidity changes**	**Predation, parasitism, disease**
Numbers									
Urban streets	79	1	19	3	30	6	11	4	18
Blue-green corridors	175	5	50	8	38	14	21	9	20
Numbers									
Small urban green spaces	135	4	38	6	39	15	22	7	20
Coastal fronts	79	0	17	2	21	5	14	3	18
Percentages									
Urban streets	35.9	1.3	24.1	3.8	38.0	7.6	13.9	5.1	22.8
Blue-green corridors	79.5	2.9	28.6	4.6	21.7	8.0	12.0	5.1	11.4
Small urban green spaces	61.4	3.0	28.1	4.4	28.9	11.1	16.3	5.2	14.8
Coastal fronts	35.9	0.0	21.5	2.5	26.6	6.3	17.7	3.8	22.8

Abbreviations: Temps., temperatures.

Concerning the specific criteria that are associated with species, again, we see very little variation between the four landscape types. As noted above for the entire dataset, sensitivity to inundation and saltwater are the most common criteria, though the former seems slightly less common among species suited to blue-green corridor landscapes and the latter seems slightly less common among species suited to urban streets and coastal front landscapes. It should also be noted that susceptibility to predation, parasitism, or disease appears to be more prominent among species suitable for urban streets and coastal fronts than among species suitable for blue-green corridors and small urban green spaces. For the remaining criteria, little variation is evident.

3.3. Key knowledge gaps

As noted above, several knowledge gaps and areas of uncertainty affected our findings. In the data collection stage of this work, it was necessary to exclude 31 species, for which no data were available. This demonstrates the need to expand the basic knowledge around potential tree species for urban planting, which will ultimately allow better-informed decisions encompassing a wider variety from which to select well-suited species.

The criteria for which data were most commonly unavailable were sensitivity to inundation, high temperatures, and saltwater, which were unknown for 106, 104, and 96 species (or 48.2%, 47.3%, and 43.6% of the total species assessed), respectively. Although all criteria had at least a few species for which data were unavailable, the three mentioned above are much higher. Existing projections indicate that these criteria are potentially the most relevant for the main impacts of climate change in Malaysia and, therefore, represent key areas for future research. ACResT will help fill some of these knowledge gaps by allowing for the assessment of more species by more practitioners. Researchers can also use it as a tool to identify the species for which tolerance is truly unknown and may need to be further studied, for example, through stress tests.

3.4. Conclusion

Our findings show that there are already urban tree species being impacted by climate change in Malaysia and that different species have varying vulnerabilities to each effect. Understanding the resilience of tree species to different climate impacts may be critical for species selection, ensuring that trees planted in Malaysian cities will be able to endure the climate of the future. Studies developed for other parts of the world, such as California, USA[18]; Shanghai, China[19]; and Australasia[20,42], are reaching similar conclusions.

This first step to assess the resilience of urban tree species to the impacts of climate change in Malaysia has limitations beyond the restricted number of species examined. More experimentation is needed, using various methodologies to expand the relevant knowledge. Studies that subject tree species to drought, root inundation, and heat stress (the climate impacts expected to be most severe in the region[43]) may be the most beneficial, considering that the future climate of Malaysian cities may be shifting towards unprecedented conditions[44]. Furthermore, these criteria were more frequently unavailable in this research, reinforcing the need for a complementary approach.

Planting and evaluating in experimental plots, as suggested by McPherson et al.[18], and documenting impacts that occur after extreme weather events can also provide insights into the climate resilience of tree species. Sensitivity to inundation is a criterion that stands out as particularly relevant in the Malaysian context[45]; changes in rainfall patterns are already manifesting, as observed with the December 2021 floods in Malaysia, which led to the displacement of more than 120,000 people[46,47]. Documenting the impacts of flooding on different tree species can substantially contribute to a better understanding of their vulnerability. The technical divisions of the government departments of impacted cities should play a role in developing and sharing these assessments.

A further approach to expand and improve knowledge of climate change resilience and vulnerability will be to develop complementary ways to document the knowledge of tree species among nursery staff, who have practical knowledge of and experience caring for various tree species. ACResT will integrate these potential follow-up studies and others that may be developed. It will also become a repository for new species assessments and documenting the impacts of climate change on trees in Malaysia, and we encourage those with an interest in the topic to contribute their knowledge and take advantage of this new resource.

Author contributions

Conceptualisation, SC and JAC; methodology, JAC; formal analysis, JAC and MS; investigation, SK; data curation, JAC, MS and TM; writing—original draft preparation, SC, JAC and MS; writing—review and editing, SC, JAC, SK, MS and TM; supervision, SC; project administration, SC and MS; funding acquisition, SC. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

References

1. Lauwaet D, De Ridder K, Saeed S, et al. Assessing the current and future urban heat island of Brussels. *Urban Climate* 2016; 15: 1–15. doi: 10.1016/j.uclim.2015.11.008
2. Estrada F, Botzen WJW, Tol RSJ. A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change* 2017; 7(6): 403–406. doi: 10.1038/nclimate3301
3. Heaviside C, Macintyre H, Vardoulakis S. The Urban Heat Island: Implications for Health in a Changing Environment. *Current Environmental Health Reports* 2017; 4(3): 296–305. doi: 10.1007/s40572-017-0150-3
4. Heaviside C, Vardoulakis S, Cai XM. Attribution of mortality to the urban heat island during heatwaves in the West Midlands, UK. *Environmental Health* 2016; 15(S1). doi: 10.1186/s12940-016-0100-9
5. Orlov A, Sillmann J, Aunan K, et al. Economic costs of heat-induced reductions in worker productivity due to global warming. *Global Environmental Change* 2020; 63: 102087. doi: 10.1016/j.gloenvcha.2020.102087
6. Zhao M, Huang X, Kjellstrom T, et al. Labour productivity and economic impacts of carbon mitigation: a modelling study and benefit-cost analysis. *The Lancet Planetary Health* 2022; 6(12): e941–e948.
7. Raymond C, Matthews T, Horton RM. The emergence of heat and humidity too severe for human tolerance. *Science Advances* 2020; 6(19). doi: 10.1126/sciadv.aaw1838
8. Toosty NT, Hagishima A, Bari W, et al. Behavioural changes in air-conditioner use owing to the COVID-19 movement control order in Malaysia. *Sustainable Production and Consumption* 2022; 30: 608–622. doi: 10.1016/j.spc.2022.01.001
9. U.S. Energy Information Administration. Air conditioning accounts for about 12% of U.S. home energy expenditures. Available online: https://www.eia.gov/todayinenergy/detail.php?id=36692 (accessed on 28 January 2022).
10. de Kleyn L, Mumaw L, Corney H. From green spaces to vital places: connection and expression in urban greening. *Australian Geographer* 2019; 51(2): 205–219. doi: 10.1080/00049182.2019.1686195
11. Lindén J, Fonti P, Esper J. Temporal variations in microclimate cooling induced by urban trees in Mainz, Germany. *Urban Forestry & Urban Greening* 2016; 20: 198–209. doi: 10.1016/j.ufug.2016.09.001
12. Zölch T, Maderspacher J, Wamsler C, Pauleit S. Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. Urban For. *Urban Green* 2016; 20: 305–316. doi: 10.1016/j.ufug.2016.09.011
13. Kardan O, Gozdyra P, Misic B, et al. Neighborhood greenspace and health in a large urban center. *Scientific Reports* 2015; 5(1). doi: 10.1038/srep11610
14. Adaptation Fund. Nature-based Climate Adaptation Programme for the Urban Areas of Penang Island. Available online: https://www.adaptation-fund.org/project/nature-based-climate-adaptation-programme-for-the-urban-areas-of-penang-island-2/ (accessed on 17 June 2022).
15. CBD Secretariat. Country profiles: Malaysia—Main Details. Available online: https://www.cbd.int/countries/profile/?country=my (accessed on 20 June 2022).
16. Saw LG, Chung RCK. The flora of Malaysia projects. *Rodriguésia* 2015; 66(4): 947–960. doi: 10.1590/2175-7860201566415
17. Ng FS, Low CM, Sanah MAN. *Endemic Trees of the Malay Peninsula. Research Pamphlet Issue 106*. Forest Research Institute Malaysia; 1990.
18. McPherson EG, Berry AM, van Doorn NS. Performance testing to identify climate-ready trees. *Urban Forestry & Urban Greening* 2018; 29: 28–39. doi: 10.1016/j.ufug.2017.09.003
19. Liu M, Zhang D, Pietzarka U, et al. Assessing the adaptability of urban tree species to climate change impacts: A case study in Shanghai. *Urban Forestry & Urban Greening* 2021; 62: 127186. doi: 10.1016/j.ufug.2021.127186
20. Marchin RM, Backes D, Ossola A, et al. Extreme heat increases stomatal conductance and drought-induced mortality risk in vulnerable plant species. *Global Change Biology* 2021; 28(3): 1133–1146. doi: 10.1111/gcb.15976
21. Jabatan Landskap Negara. Garis Panduan Landskap Negara Edisi 2. Available online: https://issuu.com/nationallandscapedepartment/docs/garis_panduan_landskap_negara_e2 (accessed on 27 May 2022).
22. Ossola A, Hoeppner MJ, Burley HM, et al. The global urban tree inventory: A database of the diverse tree flora that inhabits the world's cities. *Global Ecology and Biogeography* 2020; 29(11): 1907–1914. doi: 10.1111/geb.13169
23. Corner EJH. *Wayside Trees of Malaya in Two Volumes*, 3rd ed. Malayan Nature Society; 1988.
24. IUCN. The IUCN red list of threatened species. Version 2021-3. Available online: https://www.iucnredlist.org (accessed on 1 June 2021).
25. MyBIS. Malaysia biodiversity information system. Available online: https://www.mybis.gov.my/one/ (accessed on 1 June 2021).
26. Yong WSY, Chua LSL, Lau KH, et al. *Malaysia Red List: Plants of Peninsular Malaysia*. *Parts I and II*. Forest

Research Institute Malaysia;2021.
27. Czaja M, Kołton A, Muras P. The complex issue of urban trees—Stress factor accumulation and ecological service possibilities. *Forests* 2020; 11(9): 932. doi: 10.3390/f11090932
28. Nakamura F. Riparian forests and climate change: Interactive zone of green and blue infrastructure. In: G*reen Infrastructure and Climate Change Adaptation: Function, Implementation and Governance*. Springer Nature Singapore; 2022. pp. 73–91.
29. Toscano S, Branca F, Romano D, et al. An evaluation of different parameters to screen ornamental shrubs for salt spray tolerance. *Biology* 2020; 9(9): 250. doi: 10.3390/biology9090250
30. Lee ATK, Carr JA, Ahmad B, et al. Reforesting for the climate of tomorrow. In: *Recommendations for Strengthening Orangutan Conservation and Climate Change Resilience in Kutai National Park, Indonesia*. IUCN; 2019.
31. Foden WB, Butchart SHM, Stuart SN, et al. Identifying the world's most climate change vulnerable species: A systematic trait-based assessment of all birds, amphibians and corals. *PLoS ONE* 2013; 8(6): e65427. doi: 10.1371/journal.pone.0065427
32. Carr JA, Outhwaite WE, Goodman GL, Foden WB. *Vital but Vulnerable: Climate Change Vulnerability and Human Use of Wildlife in Africa 's Albertine Rift*. IUCN; 2013.
33. Tognelli MF, Lasso CA, Bota-Sierra CA, et al. *Conservation Status and Distribution of Freshwater Biodiversity in the Tropical Andes* (Spanish). IUCN International Union for Conservation of Nature; 2016. doi: 10.2305/iucn.ch.2016.02.en
34. Pacifici M, Foden WB, Visconti P, et al. Assessing species vulnerability to climate change. *Nature Climate Change* 2015; 5(3): 215-224. doi: 10.1038/nclimate2448
35. Foden WB, Young BE, Akçakaya HR, et al. Climate change vulnerability assessment of species. *WIREs Climate Change* 2018; 10(1). doi: 10.1002/wcc.551
36. Nenzén HK, Araújo MB. Choice of threshold alters projections of species range shifts under climate change. *Ecological Modelling* 2011; 222(18): 3346–3354. doi: 10.1016/j.ecolmodel.2011.07.011
37. Jones MC, Cheung WWL. Using fuzzy logic to determine the vulnerability of marine species to climate change. *Global Change Biology* 2017; 24(2). doi: 10.1111/gcb.13869
38. ACResT. Atlas of climate resilient tree species. Available online: https://www.acrest.com.my/ (accessed on 1 November 2022).
39. Which Plant Where. Future proof urban landscape projects with climate-ready species. Available online: https://www.whichplantwhere.com.au/ (accessed on 15 November 2022).
40. Forest Research. Right trees for changing climate database. Available online: http://www.righttrees4cc.org.uk/ (accessed on 28 October 2022).
41. Castelo S, Carr J, Khamis S, et al. Climate-resilient tree species (Climate-resilient tree species version 1). FigShare. doi: 10.6084/M9.FIGSHARE.22237561.V1
42. Burley H, Beaumont LJ, Ossola A, et al. Substantial declines in urban tree habitat predicted under climate change. *Science of The Total Environment* 2019; 685: 451–462. doi: 10.1016/j.scitotenv.2019.05.287
43. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2023. doi: 10.1017/9781009157896
44. Bastin JF, Clark E, Elliott T, et al. Correction: Understanding climate change from a global analysis of city analogues. *PLoS ONE* 2019; 14(10): e0224120. doi: 10.1371/journal.pone.0224120
45. Tang KHD. Climate change in Malaysia: Trends, contributors, impacts, mitigation and adaptations. *Science of The Total Environment* 2019; 650: 1858–1871. doi: 10.1016/j.scitotenv.2018.09.316
46. Mitchell C. Flood resilience—A time for cathedral-based thinking and action! *Journal of Flood Risk Management* 2022; 15(1). doi: 10.1111/jfr3.12780
47. Reuters. Malaysia floods caused nearly $1.5 bln in losses—govt report. Available online: https://www.reuters.com/article/malaysia-floods-idAFL4N2U81FQ (accessed on 10 February 2022).