nature portfolio

Peer Review File

Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait

Corresponding Author: Professor Ronita Bardhan

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Bardhan,

First of all, please allow me to apologise for the delay in sending a decision on your manuscript titled "Harnessing cooling from urban trees: Interconnecting background climates, urban morphology, and tree traits". It has now been seen by 4 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to
• address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid or relevant to the editorial threshold as outlined below)
AND
• meet our editorial thresholds as outlined below,

then we would be happy to look at a revised manuscript.

In the following, we list our minimum requirements for publication.

***Provide novel and fully supported insight into the cooling effects of urban trees across different climate types, urban morphology, and tree traits.

***Provide comprehensive methodological details, including clarification of your sample size and explain rationale behind the study period.

***Provide an in-depth discussion and demonstrate that that your claims are robustly supported by your data and analysis, compare your approach and findings to previous work, and address implications for planning practices.

If you choose to take up this option, please either highlight all changes in the manuscript text file or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

Link Redacted

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Martina Grecequet, PhD
Associate Editor,
Communications Earth & Environment
@CommsEarth

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements
(Download the link to your computer as a PDF.)

For Manuscripts that fall into the following fields:
• Behavioural and social science
• Ecological, evolutionary & environmental sciences
• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.zip

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper investigated the cooling effects of urban trees across different climate types, urban morphology, and tree traits. The authors aim to provide useful reference to researchers, urban planners, and policymakers in mitigating urban overheating with the planning of trees in cities. This is a topic of great significance and may attract a wide audience. I have the following observations:

1. The article was very well organized with fine finer nuances. In the method part, the authors clearly stated their research focus is on greenery in urban settings. The indices applied in assessing the cooling benefit were well defined. Here, roof gardens were mentioned but it seems that this type of building integrated greenery was not discussed separately. In addition, "...focus on their heat mitigation and modification of outdoor thermal conditions, air and surface temperatures, and thermo-physiological comfort levels..." In the article thermo-physiological aspects were not discussed in a detailed or quantitative manner.
2. Several contents of the review are merely reporting findings from specific studies. It may be more useful for the audience if comparisons between existing studies were made wherever appropriate. For example, identifying the patterns of cooling effects across different climate or urban forms. Such information would offer new insights on the cooling efficiency of urban greenery and can inform decision-making in a specific context. In the section "interconnecting background climates, urban morphology, and tree traits", the authors might consider focusing on what new understandings can be gained by reviewing work that had been done in different climate types and urban forms, and the mechanism linked to different cooling effects.
3. It may be a good idea to explore the implication for planning practice in the guiding principles for enhancing the cooling of urban trees. What can be the message to the target audience? This would highlight the contribution of this study.

Some minor comments:
• "The mechanism by which trees provide urban cooling in cities primarily involves the blockage of shortwave solar radiation during the day, leaf evapotranspiration, aerodynamic modification of surrounding airflow, and trapping of longwave radiation from the ground surface during the night as well as providing shading for humans and heat-sensitive infrastructure from direct sunlight." This is a very long sentence and a bit hard to read. Maybe break it down to several shorter sentences.
• "$\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively. These three parameters are used to quantify tree effects, indicating the combined effects of daytime shading, nighttime radiation blockage, evapotranspirational cooling, and aerodynamic resistance on outdoor thermal conditions." Not quite sure whether air temperature alone can reflect all the aspects being mentioned here. Also, would including more indices in the assessment provide a more comprehensive understanding on the cooling efficiency?
• For Figure-2, is there any extra information being provided by the graphic?
• Maybe change the subheading "Quantification of the cooling potential in four background climates" to "Quantification of the cooling potential in tropical, arid, continental, and temperate climates" for consistency.
• For the section "Leveraging multiscale modeling to support urban planning", it is not very clear now how the development of multiscale models link to urban planning.

Reviewer #2 (Remarks to the Author):

Review of "Harnessing cooling from urban trees: Interconnecting background climates, urban morphology, and tree traits"

The manuscript presents a review and meta-analysis of the cooling effect of trees, analyzing modulating factors such as urban morphology, background climate, and tree traits. This review is important as it brings together information that is otherwise available in other mini-reviews focused on different aspects of this topic. I recommend the acceptance of this manuscript following the address of the comments below:
Major:
1. The introduction lacks sufficient details on greening-heat mitigation science. How does greenery cool our environment? A clue could be the leaf energy balance, and this could be interplayed with building (urban morphology) shading effects. A graphical description may be necessary.
2. A paragraph highlighting findings from some related reviews in the last few years would be appreciated and would reinforce the need for this review.
3. I noticed that many important studies are missing from your pool. This might be linked to keywords used in the search. While "street tree" and "urban tree" were used on the greenery side, some studies may use other terms like "greening," "greenery," "vegetation" or just "trees". Similarly, on the thermal side, terms like "heat mitigation," "cooling effect," or "thermal benefit" should be included in the search. I demonstrated this by searching in sub-Saharan Africa and found interesting studies from the Federal University of Technology, Akure, Nigeria, which were not captured in the review. It's important to capture the minimal evidence from regions like this in a global review
Minor:
1. Authors should clarify the rationale behind the selected study period.
2. Some grammatical checks are advised. For instance, in the abstract, "Stomata closer."
3. There seems to be some inconsistency in the usage of certain terminology. For example, there were times when "tree trait" was used exclusively and inclusively of LAI/LAD. Additionally, tree-related indicators or factors in the Urban Morphology group across the study (see Figure 1) need clarification. How is "TD tree density" and "tree implementation" an urban morphology indicator?
4. In the methods section, the statement about trees on exterior facades needs rethinking, as it may not be feasible.
5. The effect of tree shade on energy demand or usage seems to have been overlooked, which is a key sub-topic in the discussion, especially considering the emphasis on the built environment/"Urban."
6. It would be valuable to discuss how heatwaves impact the cooling efficiency of trees and whether any studies quantify this effect.
7. Summarizing the measurement and modeling techniques/methodology/tools and expressing thoughts on these techniques may be useful, perhaps in the supplementary information.
8. On page 9, "urban greenery" was first used, which implies not just trees. Consider revising to "tree" or stating the definition of urban greening.
9. On page 10, it was mentioned that "...planned vegetation can exacerbate thermal discomfort issues in humid tropical cities." Is there only one study that addresses this, and can this statement be expressed in quantitative terms?
10. On page 11, "must be thoughtfully designed" is mentioned. Can tree species be designed?
11. On page 12, "...84 studies" were mentioned, not 131.

.

Reviewer #3 (Remarks to the Author):

The manuscript provides an original and valuable overview of the growing body of literature on the topic of local climate regulation by urban trees. Due to the high relevance of the topic, a systematic review of the existing evidence, as the one provided by the Authors, is urgently needed.

However, there are some aspects of the manuscript that need to be addressed.

General comments:
The structure of the paper should be revisited to make the content clearer, following the usual manuscript's structure consisting of introduction, methods, results, discussions and conclusion. This would help to simplify the content and avoiding some redundancy in the illustration of the results.

Specific comments:
- The numbering of the lines is missing: I recommend to add the numbering for the second round of review.
- Proofreading of minor punctuation and text inconsistencies is recommended
- page 15: it is not clear what the authors mean with absolute and relative temperature reduction. A definition of the terms is needed
- Figure 6: what do the "cont'd" and black arrows mean in the graph? It is also not clear what the Authors mean with "Tair,tree is approximated by Tair and historically observed cooling capabilities of trees in respective cities".
- Figure 7 (caption): perhaps it is redundant to add information on what the boxplots represent (e.g. that top and bottom limits of boxplots are the 25th and 75th percentile and that dots represent outliers).
- While the contribution of background climate is exhaustively represented in the manuscript with figures and tables, a schematic representation of the other factors influencing the cooling is lacking. A table or graph sumamrizing the effect of tree traits and urban morphology could be useful.

Reviewer #4 (Remarks to the Author):

I'm excited to review this manuscript since such a topic is very important for urban and urban dwellers. The author summarized recent studies to investigate the effects of urban morphology, tree traits, and climatic background on the cooling effect of urban trees. This is a significant improvement for current research since it would be a comprehensive analysis, which is critical for urban planning and management. Nevertheless, I think there are still some serious issues.
1) The sample size of only 85 papers, in my opinion, is too small for the author to do review this scientific subject, even though the author highlights some important and intriguing points. It appeared that the author has largely concentrated on the impact of climatic backgrounds. However, I find the current summary so deficient in terms of urban morphology and tree traits that it is hard for me to draw some conclusions. Although the author has summarized a few publications, these have mainly consisted of a list of findings from one or two of the articles. Can these on their own represent the findings of the current research? I'm concerned about it. For example, the author highlights how tree traits affected the cooling effect. What are the outcomes? Its cooling impact can be increased by raising LAI and LAD. Even if this is a generally acknowledged conclusion, is it unquestionable? What are the new findings of this study based on the knowledge that already exists?
2) Furthermore, I cannot find any pertinent conclusions in "internecting the climate background, tree traits, and urban morphology". Except for the results of a few publications, the author only touched on this very briefly in the guiding principles section; there was no real reviewing, that is no conclusions offered. The author may consider conducting a review based only on climate background, which is also an aspect that is currently being discussed more. In this case, the topic will be more focused, and I believe it can be further analyzed in depth.
Minor:
1) key points: the four key points, is it the result of one sample study or the reviewing results? If it is the former, I don't think it is appropriate to list it.
2) The author's objectives seem overly ambitious to me. I find it challenging to draw conclusions to respond to the research question. Where is the trade-off analysis?
3) Figure 1 is very necessary, but I think it now does not reflect the core purpose of the study. The author may consider combining the following three small figures.
4) Lines "specifically, in tropical climates, …,at only 0.31℃". It's interesting to do the comparison, but why? What are the theoretical implications of such differences? Or why?
5) Figures 4 and 5 are redundant because I think the relevant information is already reflected in Figure 6.
6) Other results are completely unsupported by charts. Some information is expressed in a list of papers. Are there any relevant and clear conclusions that can support the questions you raised earlier?

Communications Earth & Environment is committed to improving transparency in authorship. As part of our efforts in this direction, we are now requesting that all authors identified as 'corresponding author' create and link their Open Researcher and Contributor Identifier (ORCID) with their account on the Manuscript Tracking System prior to acceptance. ORCID helps the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID from the home page of the Manuscript Tracking System by clicking on 'Modify my Springer Nature account' and following the

instructions in the link below. Please also inform all co-authors that they can add their ORCIDs to their accounts and that they must do so prior to acceptance.
https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research

For more information please visit http://www.springernature.com/orcid

If you experience problems in linking your ORCID, please contact the Platform Support Helpdesk.

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Bardhan,

Your manuscript titled "Harnessing cooling from urban trees: Interconnecting background climates, urban morphology, and tree traits" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. In particular for publication in Communications Earth & Environment we request that you outline importance of your findings and the overall benefit and discuss how your research questions differ from previous studies. At the same time, we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication. For further information about article processing charges, open access funding, and advice and support from Nature Research, please visit https://www.nature.com/commsenv/open-access

At acceptance, you will be provided with instructions for completing the open access licence agreement on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Martina Grecequet, PhD

Senior Editor,
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Congrats to the authors that this revised manuscript is more comprehensive and provided new perspectives from a more "organic' review. However, it is not very clear why do we need to know these findings? Who will benefit from them? Are the research questions largely different from previous ones? In this matter, the significance and novelty of the study have not reached the high standards of this journal.

Reviewer #3 (Remarks to the Author):

I would like to thanks the Authors for addressing my comments.
I consider that the manuscript has improved according to the suggestion and I would like to recommend for its acceptance.
Kind regards

Reviewer #4 (Remarks to the Author):

I appreciate the author’s responses to my concerns regarding a small number of papers in this review. My main worry was that some relevant papers might have been missed, as the first version focused largely on the effects of climate on temperature reduction, while the authors aim to explore the combined effects of climate, urban morphology, and tree traits. Now, thank you for the very clear methods section. I now have a full understanding of the review process, as will the readers. All my concerns have been addressed in this revision.
I have just one minor suggestion. Since the authors mentioned a review covering articles published before 2010 and have now focused on papers published after 2010, are there any significant differences in findings between these two reviews? If so, I suggest the authors highlight them. If not, no further detail is needed. Overall, I recommend publication, as this comprehensive review on temperature reduction, integrating these factors, would provide valuable guidance to urban planners and policymakers.

This paper investigated the cooling effects of urban trees across different climate types, urban morphology, and tree traits. The authors aim to provide useful reference to researchers, urban planners, and policymakers in mitigating urban overheating with the planning of trees in cities. This is a topic of great significance and may attract a wide audience. I have the following observations:

1. The article was very well organized with fine finer nuances. In the method part, the authors clearly stated their research focus is on greenery in urban settings. The indices applied in assessing the cooling benefit were well defined. Here, roof gardens were mentioned but it seems that this type of building integrated greenery was not discussed separately. In addition, "...focus on their heat mitigation and modification of outdoor thermal conditions, air and surface temperatures, and thermo-physiological comfort levels..." In the article thermo-physiological aspects were not discussed in a detailed or quantitative manner.

2. Several contents of the review are merely reporting findings from specific studies. It may be more useful for the audience if comparisons between existing studies were made wherever appropriate. For example, identifying the patterns of cooling effects across different climate or urban forms. Such information would offer new insights on the cooling efficiency of urban greenery and can inform decision-making in a specific context. In the section “interconnecting background climates, urban morphology, and tree traits”, the authors might consider focusing on what new understandings can be gained by reviewing work that had been done in different climate types and urban forms, and the mechanism linked to different cooling effects.

3. It may be a good idea to explore the implication for planning practice in the guiding principles for enhancing the cooling of urban trees. What can be the message to the target audience? This would highlight the contribution of this study.

Some minor comments:

- “The mechanism by which trees provide urban cooling in cities primarily involves the blockage of shortwave solar radiation during the day, leaf evapotranspiration, aerodynamic modification of surrounding airflow, and trapping of longwave radiation from the ground surface during the night as well as providing shading for humans and heat-sensitive infrastructure from direct sunlight.” This is a very long sentence and a bit hard to read. Maybe break it down to several shorter sentences.
- “$\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively. These three parameters are used to quantify tree effects, indicating the combined effects of daytime shading, nighttime radiation blockage, evapotranspirational cooling, and aerodynamic resistance on outdoor thermal conditions.” Not quite sure whether air temperature alone can reflect all the aspects being mentioned here. Also, would including more indices in the assessment provide a more comprehensive understanding on the cooling efficiency?
- For Figure-2, is there any extra information being provided by the graphic?
- Maybe change the subheading “Quantification of the cooling potential in four background climates” to “Quantification of the cooling potential in tropical, arid, continental, and temperate climates” for consistency.
- For the section “Leveraging multiscale modeling to support urban planning”, it is not very clear now how the development of multiscale models link to urban planning.

Rebuttal to Reviewers

Reviewer #1 (Remarks to the Author): This paper investigated the cooling effects of urban trees across different climate types, urban morphology, and tree traits. The authors aim to provide useful reference to researchers, urban planners, and policymakers in mitigating urban overheating with the planning of trees in cities. This is a topic of great significance and may attract a wide audience.

Response to Reviewer #1: We appreciate the thorough review of our work and providing feedback. We have addressed the points raised and hope that the quality of the manuscript has been significantly improved. The reviewer's comments are highlighted in **bold black**, and all revisions are highlighted in blue below and in the revised manuscript.

I have the following observations:

1. The article was very well organized with fine finer nuances. In the method part, the authors clearly stated their research focus is on greenery in urban settings. The indices applied in assessing the cooling benefit were well defined. Here, roof gardens were mentioned but it seems that this type of building integrated greenery was not discussed separately. In addition, "...focus on their heat mitigation and modification of outdoor thermal conditions, air and surface temperatures, and thermo-physiological comfort levels..." In the article thermo-physiological aspects were not discussed in a detailed or quantitative manner.

Response: The main body of the meta-analysis has been focused on pedestrian-level urban heat mitigation, which does not include the heat mitigation of roof gardens. Nevertheless, it is an important feature, especially for compact urban forms. We extended the discussion on their unique cooling benefits and how they compare to other types of urban greenery.

Our meta-analysis is mainly based on air temperature reduction at the pedestrian level (accounting for 126 studies, ~70%). To cover the thermo-physiological aspects, we presented the quantitative analysis of thermal comfort indicators in **Figure 5**, and we also emphasized the importance of multi-variable analysis in the discussion section.

Revision: Line 97-102

Urban trees have been utilized in various urban planning and landscape design applications, such as urban streets, roof gardens, and other integrations with buildings, residential areas, campuses, and urban parks [1]. In this study, to quantitatively assess their cooling effectiveness, we exclude research that solely focuses on trees planted in urban parks or integrated at rooftops, as in such locations, the impact of tree shading and evapotranspiration on pedestrian level is trivial or difficult to isolate.

Revision: Line 432-444

Although a higher degree of tree canopy cover in street canyons generally results in more significant cooling effects, excessively high tree canopy cover may trap heat at the pedestrian level, especially in LCZ 1-3 compact zones with high background temperature climates [2]. Due to stomatal closure and the absence of solar radiation, transpirational cooling and shading are minimal at nighttime. Improper extensive planting of trees can result in low SVF and weakened micro-scale air ventilation, which causes the trapping of longwave radiation beneath the tree foliage[3–5]. Therefore, in compact urban zones, narrow species and sparse planting strategies are recommended. Additionally, tree species with smaller root systems that fit into limited spaces without causing structural damage to buildings are ideal for roof or terrace gardens. Recent research has demonstrated that integrated greenery provides effective cooling effects and is of vital importance, especially in densely built urban areas (LCZ 1-3) where open ground space is often scarce[6–9]. Trees on building roofs or terraces can effectively block radiation to building surfaces, add aerodynamic resistance, and cool surfaces through shading and evapotranspiration, providing a 1.8–4°C cooling effect at roofs and up to 15°C for indoor temperature reduction[6,7].

Revision: Line 344-348

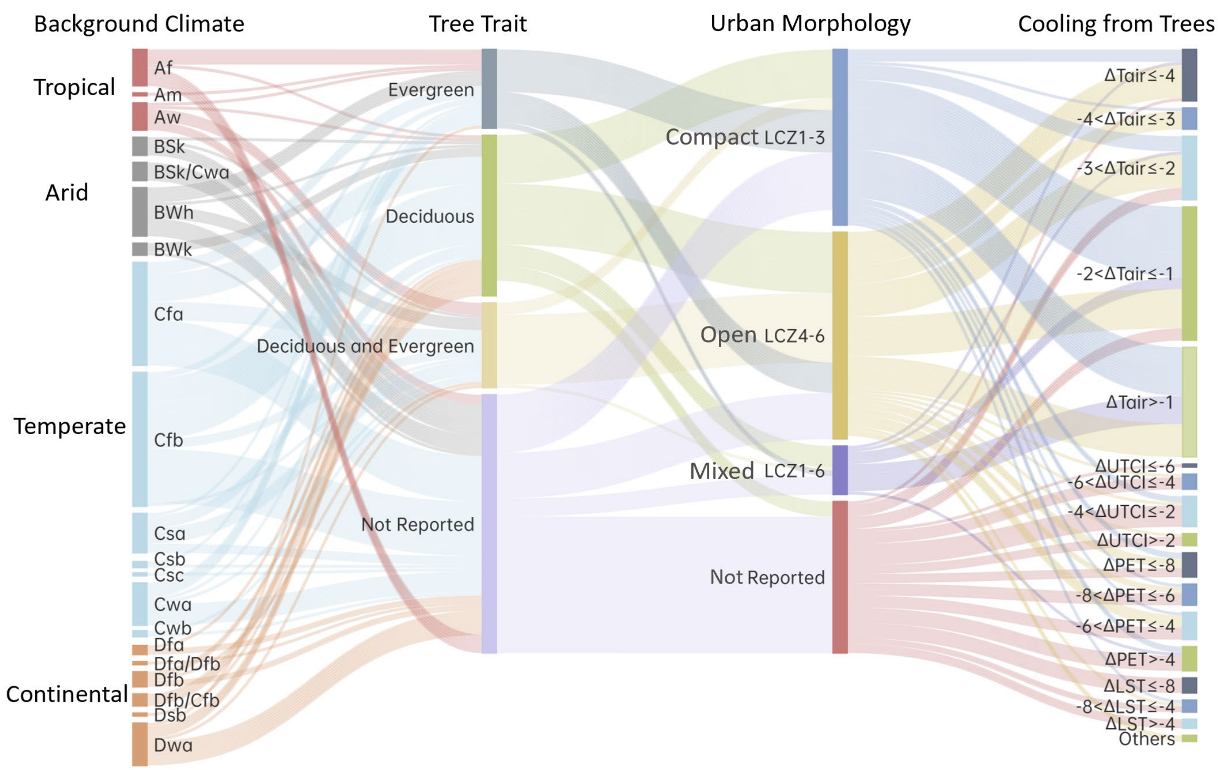

Figure 5. The hidden interconnections of background climate, tree traits, urban morphology characteristics, and the corresponding cooling potentials. The tree traits are characterized by leaf retention types and the urban morphology characteristics are characterized by local climate zone (LCZ). The cooling potential is evaluated using indicators including ΔT_{air}, ΔUTCI, ΔPET, and ΔLST.

Revision: Line 368-375

From **Figure 5**, urban tree cooling is primarily quantified by air temperature reduction (ΔT_{air}, 126 case studies). In addition, 30% of studies mainly focused on thermal comfort or thermo-physiological comfort analysis, often using indicators such as UTCI (25 studies) and PET (48 studies). As an example, UTCI calculation (Eq.2) incorporates air temperature (T_{air}), and additional meteorological variables such as relative humidity (RH), wind speed (V_{air}), and mean radiant temperature (T_{mrt}) [10]. Moreover, a few meso-scale remote sensing studies quantified cooling from trees solely based on land surface temperature (LST). The UTCI changes can reach up to -6°C, with most changes ranging from -4°C to -2°C. Similarly, the PET changes can reach up to -8°C, typically ranging from -8°C to -4°C.

$$UTCI = T_{air} + f(T_{air}, T_{mrt}, V_{air}, RH) \quad (2)$$

Revision: Line 526-531

Future research should leverage multi-variable analysis. Urban climates are influenced by a multitude of factors, including temperature, humidity, wind speed, solar radiation, and pollution levels[11,12]. Thermal comfort or thermo-physiological variables, such as UTCI and PET, are closely linked to heat-related health issues, particularly to quantify the risks for vulnerable populations such as older people, children, and those with pre-existing health conditions[11,13,14]. Utilizing multi-variable analysis is key to human-centered designs and interventions to enhance overall well-being.

2. Several contents of the review are merely reporting findings from specific studies. It may be more useful for the audience if comparisons between existing studies were made wherever appropriate. For example, identifying the patterns of cooling effects across different climate or urban forms. Such information would offer new insights on the cooling efficiency of urban greenery and can inform decision-making in a specific context. In the section "interconnecting background climates, urban morphology, and tree traits", the authors might consider focusing on what new understandings can be gained by reviewing work that had been done in different climate types and urban forms, and the mechanism linked to different cooling effects.

Response: Thank you for the suggestions. We have restructured and revised the section "Interconnections between climate, urban morphology, and tree traits."

Revision: Line 270-396

Interconnections between climate, urban morphology, and tree traits

Most research focuses on case studies in specific study sites with distinct local climates. Consequently, there is a notable gap in systematically studying the integration of background climates, tree traits, and urban morphology factors. This section aims to provide a comprehensive understanding through a quantitative meta-analysis of interconnected factors that collectively determine the cooling benefits of urban trees.

Diurnal cooling effects in tropical, arid, continental, and temperate climates

We synthesize the key case studies for meta-analysis in **Figure 3**. The cooling effects of trees in these studies are quantitatively analyzed in terms of $\Delta T_{air,max}$ and $\Delta T_{air,mean}$ across different climates, spatial scales (micro, local, and meso), and methods (measurement and simulation). Selected factors are also summarized in **Figure 3**, including leaf retention type as a tree trait and local climate zone (LCZ) as an urban morphology characteristic.

Figure 3 demonstrates that the reviewed studies encompass a wide range of urban morphology types and a diverse variety of tree types across different climates. For tropical climates, observed daily maximum temperature change $\Delta T_{air,max}$ varies between -12 °C (cooling) and +0.8 °C (warming). Specifically, the maximum daytime cooling effects of trees can reach up to -5°C in Thailand[15], -5.6°C in India[16], and -12°C in Nigeria[17], in Aw climate. However, in tropical rainforest climates (Af), where humidity is higher, the cooling effect drops to approximately a mean value of -2 °C. The cooling potential of urban trees in arid climates is also significant, with observed $\Delta T_{air,max}$ reaching up to -9.3 °C (cooling), as shown in **Figure 3**. It is worth noting that a minor warming effect (+0.4 °C) can occur during the nighttime in these arid climates. In continental climates, the cooling potential can reach up to -5.7 °C (**Figure 3**), although nighttime warming effects are frequently reported in Dfb (humid continental) climates [18,19]. In temperate climates, the range of observed ΔT_{air} varies from -6.00 °C (cooling) to +1.50 °C (warming).

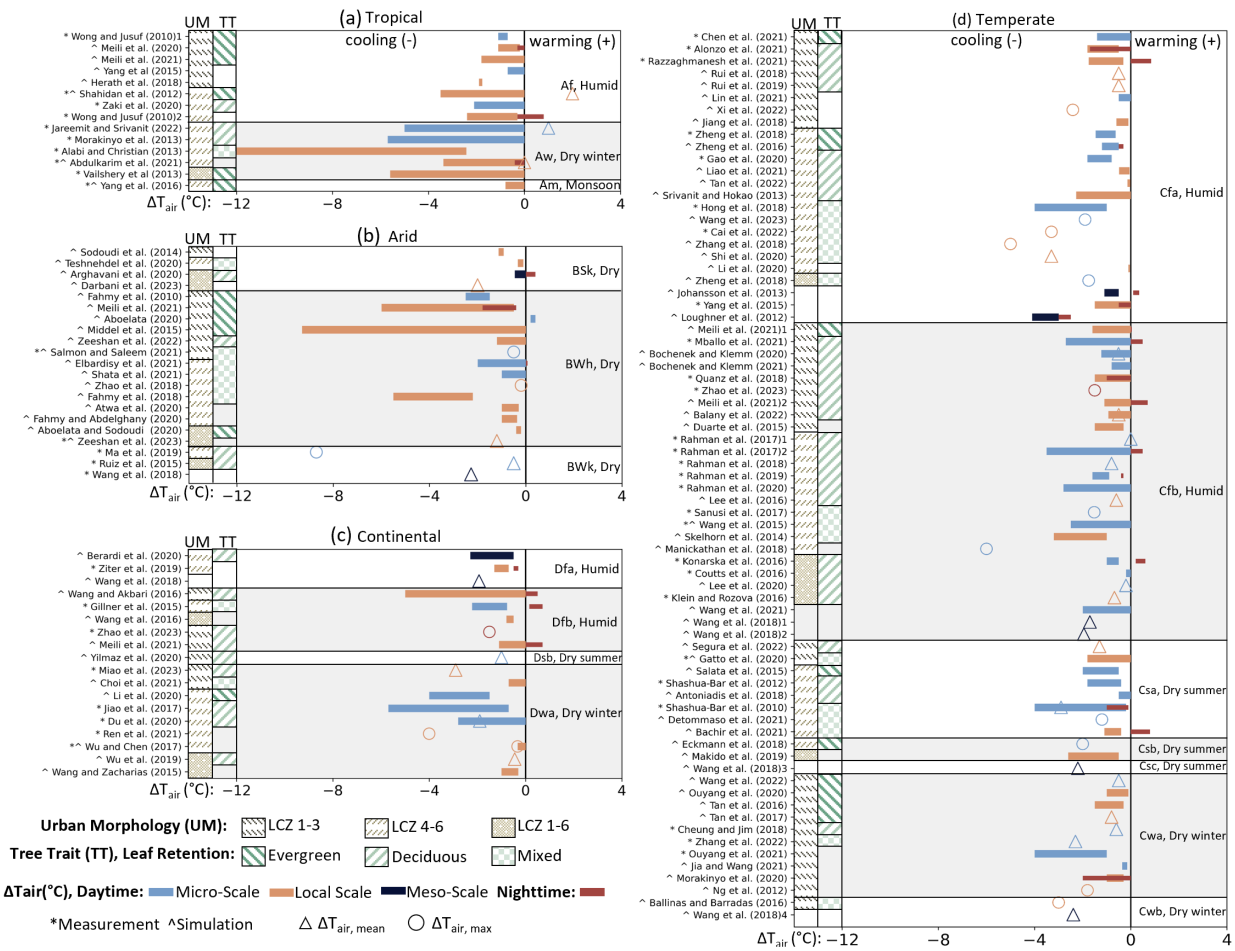

Figure 3. Diurnal variation of ΔT_{air} observed in the (a) tropical, (b) arid, and (c) continental climates. The plotted bars and markers (triangle/circle) represent the cooling or warming efficacy, and the shades in blue, orange and black colors represent the spatial scales on which the cooling or warming was observed. The nighttime effects caused by trees are presented in red. The studies are also classified based on urban morphology (represented by LCZ), tree traits (represented by leaf retention types), and methodologies (measurement or simulation).

The precipitation difference among the sub-climate types affects the cooling of trees. On average, tropical wet climates (Aw) exhibit more significant cooling benefits from trees compared to tropical rainforest climates (Af). This is due to the higher year-round humidity levels in Af. The $\Delta T_{air,max}$ difference between dry (Aw) and humid (Af) climates is as significant as 2.12 °C. However, in temperate climates, the $\Delta T_{air,max}$ difference between dry (Csa and Csb) and humid (Cfa, Cfb, Cwa, and Cwb) climates is negligible, at only 0.28 °C.

Studies show that a higher diversity of plant use, particularly the mixed use of various sizes of evergreen and deciduous trees, is linked to open urban forms (LCZ 4-6), often resulting in more significant cooling in tropical, temperate, and continental climates. The combined use of deciduous and evergreen trees generally results in 0.5°C higher cooling compared to studies using only deciduous or evergreen trees in these climates. In arid climates, studies with solely evergreen trees show higher tree cooling potential.

These studies provide convincing evidence that the cooling benefits of trees during the daytime are significant in tropical, arid, and continental climates. However, minor warming effects can be observed in some cases during the nighttime in continental climates. The reduction in cooling or minor warming effects during the nighttime can be caused by stomatal closure, reduced heat removal due to aerodynamic resistance, and the trapping of longwave radiation beneath the tree canopy[20,21].

Results in different spatial scales with different methods may exhibit disparities (**Figure 3**), as micro-scale studies focus on individual or idealized street canyons, while local scale studies investigate neighborhood areas with realistic urban morphology. Flows in the micro- and local scales are primarily dominated by mesoscale flows[22,23]. Meso-scale (2 km up to 2000 km) flows are regulated by land and sea breeze circulations in coastal areas, thermally induced valley winds, and channeled flow along valleys[24]. At the micro- and local scale, airflow in the street canyon plays a crucial role in facilitating ventilation, heat removal, and pollutant dispersion.

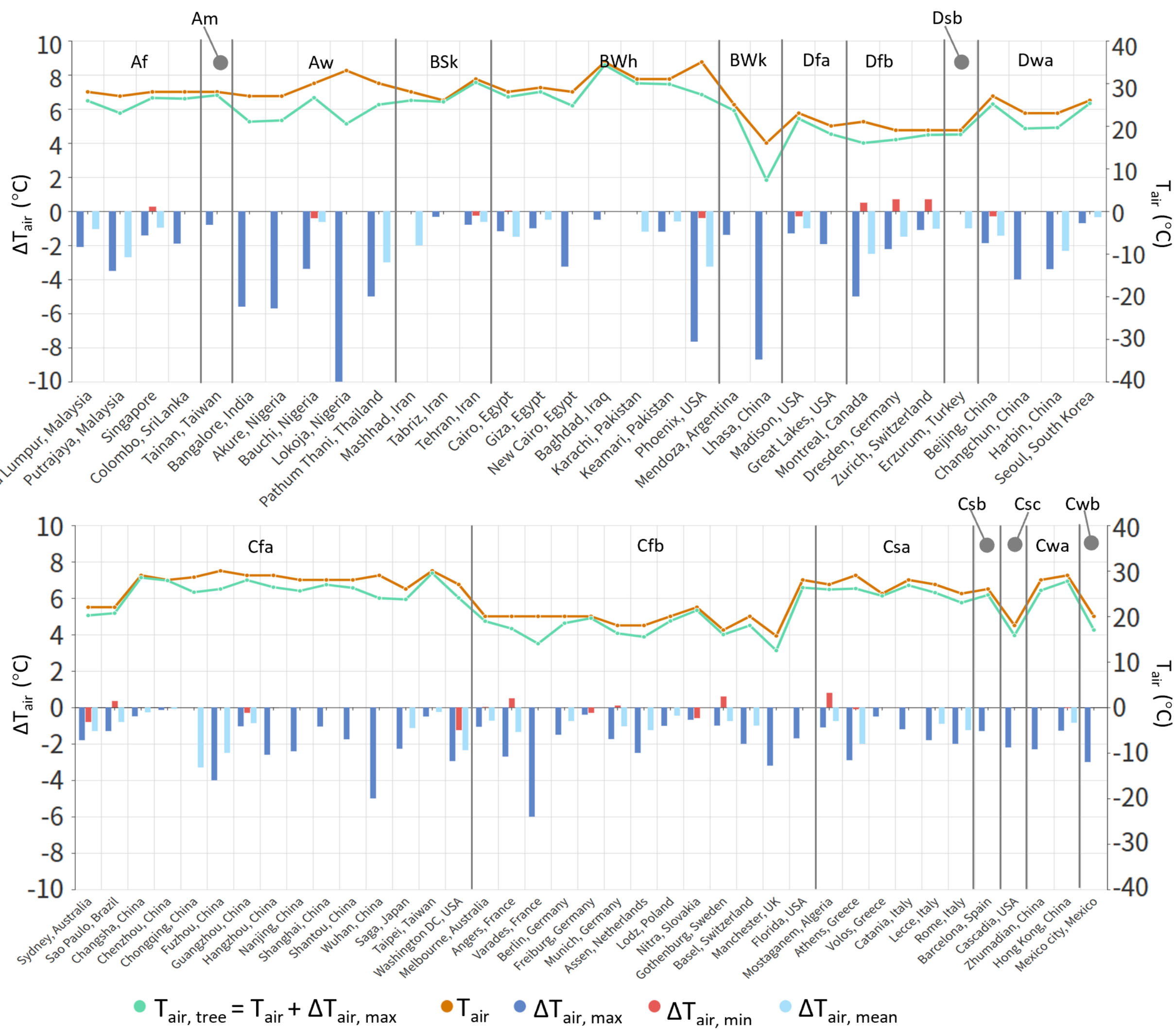

Figure 4. Estimated urban tree cooling potential in 71 major cities or regions. Solid lines compare the achievable air temperature with urban trees ($T_{air,tree}$, green line referring to the right axis) vs. the historically hottest month air temperature observed in the reviewed studies (T_{air}, orange line referring to the right axis). $T_{air,tree}$ represents a lower air temperature cooled by trees, which equals the sum of the historically hottest month air temperature observed (T_{air}) and achievable air temperature reductions ($\Delta T_{air,max}$, blue bar referring to the left axis). Bars in dark blue, red, and light blue represent the reported cooling benefits characterized by $\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively.

Studies on the micro and local scales (up to 2 km) take up more than 80% of the studies, as summarized in **Supplementary C**. **Figure 4** highlights the estimated urban tree cooling potential based on micro and local scale studies. In particular, we report cooling benefits ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) in each city. After the implementation of trees, in 83% of cities, the air temperature of the hottest month was reduced to below 26 °C, meeting the thermal comfort threshold[25].

When comparing absolute temperature reduction (ΔT_{air}) and relative temperature reduction ($\Delta T_{air}/T_{air}$), trees in tropical and arid climates demonstrate more significant cooling effects in absolute terms, while trees in continental and temperate climates offer a higher relative air temperature reduction. In other words, the proportional reduction of air temperature by trees in continental and temperate climates is more pronounced. Therefore, future urban planning initiatives should consider both the relative and absolute impacts of trees' cooling potential concerning local background climates. This approach will enable the implementation of targeted strategies that maximize the cooling potential of trees in respective climates.

Quantification of tree cooling effects influenced by interconnected factors

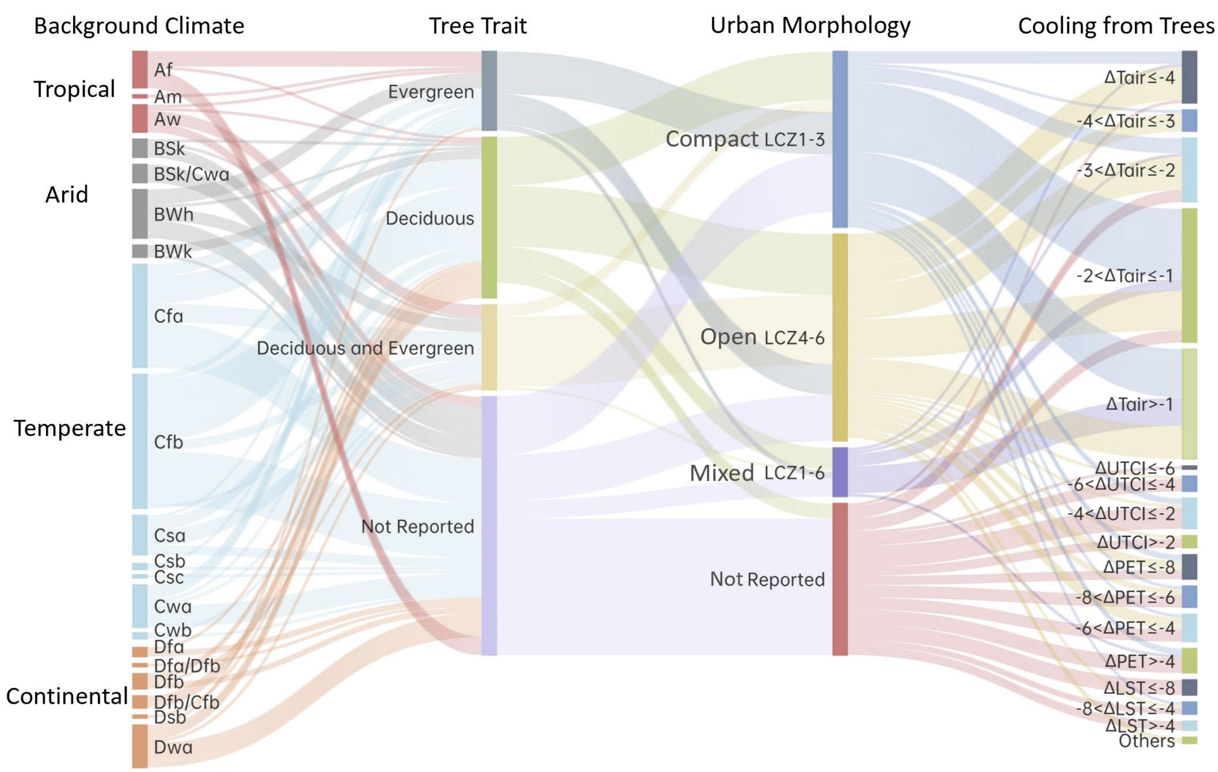

Figure 5. The hidden interconnections of background climate, tree traits, urban morphology characteristics, and the corresponding cooling potentials. The tree traits are characterized by leaf retention types and the urban morphology characteristics are characterized by local climate zone (LCZ). The cooling potential is evaluated using indicators including ΔT_{air}, ΔUTCI, ΔPET, and ΔLST.

Background climate, urban morphology, and tree traits are highly interconnected and can collectively determine urban tree cooling potentials (**Figure 5**). Among the reviewed studies, urban trees in tropical climates are predominantly evergreen. In compact urban forms (LCZ1-3), all studies involve evergreen trees, while in open urban forms (LCZ4-6), 27% of studies involve evergreen trees, 57% involve deciduous trees, and 16% involve mixed species (**Figure 6**). Deciduous trees in tropical and arid climates shed their leaves typically in response to dry seasons rather than cold temperatures[26]. In arid climates, evergreen trees are dominant; around 80% of studies involve evergreen trees, and 20% involve deciduous trees. In temperate and continental climates, there is a mixed use of deciduous and evergreen trees. Tree traits, whether evergreen, deciduous, or a mix of both, are linked to various types of urban morphology, showing a broad distribution across compact, open, and mixed urban forms (**Figure 5**). About 25% of the reviewed articles neither report urban morphology information nor specify tree types.

The cooling effects from trees are quantified in complex dimensions. These results indicate significant variations in tree effects across different climates in terms of cooling efficacy (**Figure 6**). According to the 75th and 25th percentiles of the boxplot, trees exhibit distinct ranges of cooling efficacy ($\Delta T_{air,max}$ and $\Delta T_{air,mean}$) across different climates, which are affected by local weather patterns. In arid climates, the cooling efficacy has an extensive range. The high cooling efficacy is due to high shading potential with low latitudes and high transpirational potential with a high vapor pressure deficit[21], while low cooling efficacy is due to various environmental stressors such as extreme temperatures, dry air and soil, and low tree survival rates [27].

From **Figure 5**, urban tree cooling is primarily quantified by air temperature reduction (ΔT_{air}, 126 case studies). In addition, 30% of studies mainly focused on thermal comfort or thermo-physiological comfort analysis, often using indicators such as UTCI (25 studies) and PET (48 studies). As an example, UTCI calculation (Eq.2) incorporates air temperature (T_{air}), and additional meteorological variables such as relative humidity (RH), wind speed (V_{air}), and mean radiant temperature (T_{mrt}) [10]. Moreover, a few meso-scale remote sensing studies quantified cooling from trees solely based on land surface temperature (LST). The UTCI changes can reach up to -6°C, with most changes ranging from -4°C to -2°C. Similarly, the PET changes can reach up to -8°C, typically ranging from -8°C to -4°C.

$$UTCI = T_{air} + f(T_{air}, T_{mrt}, V_{air}, RH) \quad (2)$$

Studies, in general, show stronger urban tree cooling in open and low-rise areas in dry climates (**Figure 6**). With open urban form LCZ 4-6, the cooling can be improved by about 0.4 °C (**Table 1**). This is mainly due to the availability of larger spaces that allow for greater canopies, higher biodiversity, and more extensive green coverage. On average (as seen in **Table 1**), the temporal mean air temperature, $T_{air,mean}$, shows a higher reduction (-2.14 °C) in arid climates with LC Z4-6, while it is at its lowest (-1.03 °C) in temperate climates with LCZ 1-3. Case studies with mixed-use trees in open urban morphology zones (LCZ4-6) yield more significant cooling effects than those in compact urban morphology zones (LCZ1-3), especially in hot and warm dry climates. These results emphasize the importance of strategic urban planning that incorporates diverse tree types and extensive green spaces to maximize cooling benefits, especially in arid and high-temperature regions.

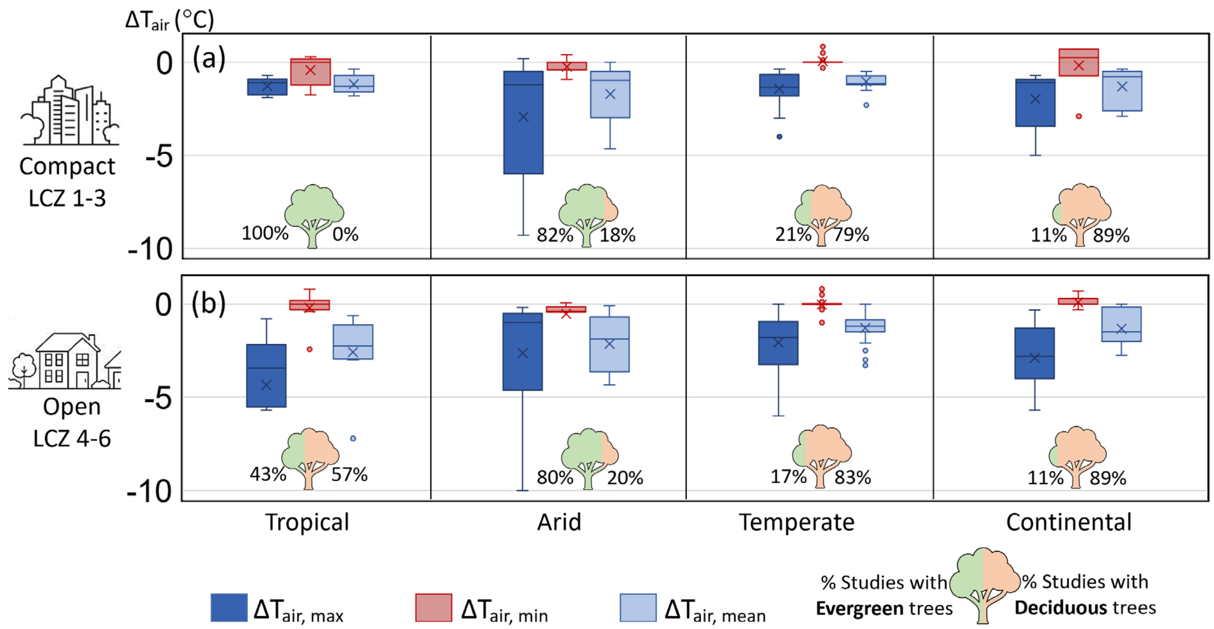

Figure 6. The cooling potential of urban trees evaluated across complex dimensions. The box plots display maximum ($\Delta T_{air,max}$, dark blue), minimum ($\Delta T_{air,min}$, red), and mean ($\Delta T_{air,mean}$, light blue) air temperature reductions and the use of evergreen and deciduous trees, for compact and open urban morphology as well as in tropical, arid, temperate, and continental climates. The box plot's rectangle covers the interquartile range (25th to 75th percentiles). Inside, lines mark the median, and a cross marks the mean. Whiskers extend to the data's minimum and maximum within 1.5 times the interquartile range.

Table 1. Summary of reported cooling efficacy ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) of studies averaged for compact (LCZ 1-3) and open (LCZ 4-6) urban forms, and in tropical, arid, temperate and continental climate groups.

Tropical		**$\Delta T_{air,\ max}$ (°C)**	**$\Delta T_{air,\ min}$ (°C)**	**$\Delta T_{air,\ mean}$ (°C)**
LCZ 1-3	Compact	-1.28	-0.42	-1.18
LCZ 4-6	Open	-4.36	-0.21	-2.57
Arid		**$\Delta T_{air,\ max}$ (°C)**	**$\Delta T_{air,\ min}$ (°C)**	**$\Delta T_{air,\ mean}$ (°C)**
LCZ 1-3	Compact	-2.92	-0.25	-1.72

LCZ 4-6	Open	-2.83	-0.52	-2.14
Temperate		**$\Delta T_{air, max}$ (°C)**	**$\Delta T_{air, min}$ (°C)**	**$\Delta T_{air, mean}$ (°C)**
LCZ 1-3	Compact	-1.42	0.05	-1.03
LCZ 4-6	Open	-2.07	-0.04	-1.33
Continental		**$\Delta T_{air, max}$ (°C)**	**$\Delta T_{air, min}$ (°C)**	**$\Delta T_{air, mean}$ (°C)**
LCZ 1-3	Compact	-1.97	-0.20	-1.31
LCZ 4-6	Open	-2.91	0.14	-1.55

3. It may be a good idea to explore the implication for planning practice in the guiding principles for enhancing the cooling of urban trees. What can be the message to the target audience? This would highlight the contribution of this study.

Response: Thank you for the suggestions on "Guiding principles for enhancing the cooling of urban trees". We have revised it accordingly to emphasize the guiding principles in selecting tree species and optimizing tree placement with an integrated approach.

Revision: Line 397-496

Guiding principles for harnessing cooling effects of urban trees

Findings from our systematic review meta-analysis have important implications for urban heat mitigation practices. We proposed an integrated approach to align key practices, such as tree selection and tree placement, with urban morphology and background climate. We further elaborate on tree-planning strategies for a warming future climate and discuss recent international and national tree-planning initiatives.

An integrated approach: aligning tree selection and placement with urban morphology and climate

"Right tree, right place." The selection of appropriate tree species and their placement in appropriate locations should be based on the available space, growth requirements, and suitable climate conditions to maximize the cooling impact.

This approach ensures that local species can thrive and provide maximum cooling benefits. In general, tree species and the age of the tree determine leaf retention, LAI, LAD, and tree crown morphology, which collectively influence the cooling efficacy of a single tree. In tropical, temperate, and continental climates, reviewed studies show higher biodiversity with various heights of deciduous and evergreen trees. The mixed-use of various species can balance seasonal shading and sunlight, providing three-dimensional cooling at various heights[5,28]. From the reviewed studies, low stomatal resistance species such as *Ulmus americana* can maximize transpiration, though these species are less common in arid climate zones[29]. In high-temperature climates, small-leaved, heat-resistant species such as *Gleditsia triacanthos* L. and *Metasequoia glyptostroboides* are recommended[30]. In dry climates, prioritizing drought-resistant evergreens that maximize shading and tree-trait-driven cooling is crucial[19]. Higher LAI and LAD values of trees correlate with higher cooling potential during the daytime, as the radiation blockage effects of trees are enhanced [31,32]. Variations in air temperature and sensible heat flux, along with the enhancements in latent heat flux, exhibit a non-linear dependency on LAI[33]. The cooling effects also increase nonlinearly with tree height in symmetrical street canyons [34].

Furthermore, the selection of species and tree placement needs to comply with the urban forms. Trees are expected to provide effective cooling at hot spots in cities; therefore, it is suggested that high leaf-density species be planted densely to offer more coverage at hot spot locations, considering the street orientation, airflow patterns, etc. The orientation of the street canyon, LCZ, aspect ratio, SVF, and other urban morphology features that significantly influence the effects of trees should be carefully considered[35–37]. In compact urban forms with relatively low greenery fraction, especially in LCZ 1, trees usually exhibit high vertical growth and narrow crowns; in comparison, in open canopies LCZ 4-6, trees are often planted densely with spreading crowns [30,38], which are more suitable for deciduous trees. The cooling effects of trees increase with tree canopy coverage, which in turn influences SVF beneath trees[33]. Nevertheless, a denser tree arrangement can lead to improved cooling benefits[39]. For example, in Saga, Japan, a 20% increase in the density of trees resulted in a -2.27 °C reduction in air temperature at the peak temperature on a university campus[40].

Although a higher degree of tree canopy cover in street canyons generally results in more significant cooling effects, excessively high tree canopy cover may trap heat at the pedestrian level, especially in LCZ 1-3 compact zones with high background temperature climates [2]. Due to stomatal closure and the absence of solar radiation, transpirational cooling and shading are minimal at nighttime. Improper extensive planting of trees can result in low SVF and weakened micro-scale air ventilation, which causes the trapping of longwave radiation beneath the tree foliage[3–5]. Therefore, in compact urban zones, narrow species and sparse planting strategies are recommended. Additionally, tree species with smaller root systems that fit into limited spaces without causing structural damage to buildings are ideal for roof or terrace gardens. Recent research has demonstrated that integrated greenery provides effective cooling effects and is of vital importance, especially in densely built urban areas (LCZ 1-3) where open ground space is often scarce[6–9].

Trees on building roofs or terraces can effectively block radiation to building surfaces, add aerodynamic resistance, and cool surfaces through shading and evapotranspiration, providing a 1.8–4°C cooling effect at roofs and up to 15°C for indoor temperature reduction[6,7].

Urban trees for heat mitigation in a warming climate

As one of the key factors in the integrated approach, background climates are essential to the cooling effects of urban trees [41,42], which regulate the cooling efficacy and influence the selection of appropriate species. Embedding climatic factors in urban planning and tailoring tree-planting strategies is crucial, especially in the face of global warming.

Our meta-analysis illustrates the significance of background temperature and precipitation on the cooling effects of trees in tropical climates [43]. Cities in arid and tropical climates, generally located at lower latitudes, are subject to intense solar irradiance and high background air temperatures[21,44]. Our findings align with those of Yang et al.[45] and Su et al.[46], demonstrating that the cooling efficacy of trees varies markedly among cities, with higher values attained in hot and dry cities. Given that the vapor pressure within the stomata is near the saturation vapor pressure at the leaf temperature, the potential for transpirational cooling in hot climates is significant and, meanwhile, highly sensitive to environmental humidity levels. Wang et al.[47] conducted meso-scale numerical simulations and compared the near-surface temperature with/without trees across the contiguous United States. Among the six regions, it was found that regions in temperate oceanic climate have relatively lower cooling potential than other climate types.

Given current global warming and increasing precipitation, it is becoming increasingly imperative to reform urban planning policies to embed climate-specific strategies and adapt to future warming. Urban planners should consider choosing resilient species that can thrive in changing climate conditions. Heatwaves can strain trees by increasing their water demand while simultaneously reducing water availability due to higher evapotranspiration rates. Exceptionally high temperatures and extremely high vapor pressure deficits at the hottest hours can cause stomatal closure, which reduces transpirational cooling [21,48,49], particularly in tropical and arid climates. Studies have quantified that during heatwaves, the cooling benefits of urban trees could decrease by up to 30% due to stress-induced stomatal closure and water scarcity[50,51]. This reduction in transpiration can significantly affect the microclimate benefits provided by urban forests, making cities more vulnerable to heat stress. Additionally, prolonged heat stress can lead to tree mortality, further diminishing urban canopy cover and exacerbating the heat island effect. This phenomenon highly depends on tree species. Urban planners should plan for future warmer climates by choosing resilient species, such as anisohydric species, that can thrive in changing climate conditions[52].

On the other hand, trees may take decades to fully mature and deliver the full magnitude of their expected shading benefits[53,54]. Young trees with smaller crowns and root systems may not provide expected shading and may even struggle to survive during hot summers[55]. Given the urgency of global warming and its consequences, waiting for trees to mature over a long period may not be practical. Therefore, when implementing urban trees, it is critical to enhance cooling effects by optimizing tree traits with the consideration of the growth time required. Other complementary shading and evaporation solutions, such as solar shading and reflective materials, are essential in combating future detrimental urban overheating in the short term.

Several international and national tree-planting initiatives have focused on the strategic selection and placement of trees. Most of the initiatives are designed to enrich biodiversity and climate resilience. In Hong Kong, the government's Plantation Enrichment Programme has been instrumental in introducing both exotic and native tree species to improve ecological health upstream and minimize the tree risks downstream[56,57]. Projects like the European Union's 3 Billion Trees initiative encourage the creation of green corridors and urban forests[58]. These initiatives focus on planting trees in a way that connects different green spaces, enhancing the cooling effect across more expansive urban areas. Cities like Singapore have integrated tree planting into their urban planning policies, emphasizing the creation of green roofs and vertical gardens in addition to traditional tree planting. Some cities focus on planting heat-resilient species. For example, cities in Australia have promoted local species like the Australian eucalyptus and various native trees, which are known for their ability to withstand high temperatures[59].

Our study serves as a database platform that documents global tree-related urban heat mitigation cases, which can facilitate the identification of native tree species and the evaluation of their cooling performance. Adaptation strategies should focus on nature-based solutions that promote local biodiversity and integration with urban infrastructures. Governments can benefit from our study by implementing policies to encourage the planting of native species that are well-adapted to both current and future climate conditions.

Some minor comments:

• "The mechanism by which trees provide urban cooling in cities primarily involves the blockage of shortwave solar radiation during the day, leaf evapotranspiration, aerodynamic modification of surrounding airflow, and trapping of longwave radiation from the ground surface during the night as well as providing shading for humans and heat-sensitive infrastructure from direct sunlight." This is a very long sentence and a bit hard to read. Maybe break it down to several shorter sentences.

Revision: Line 61-64

Trees provide urban cooling in cities via several key mechanisms. During the day, trees provide shading by blocking shortwave solar radiation; their leaves perform evapotranspiration; and the foliage also modifies the surrounding airflow aerodynamically[20,55,60,61]. At night, spacious crowns of trees can trap longwave radiation from the ground surface[20,30,62].

• "ΔTair,max, ΔTair,min, and ΔTair,mean, respectively. These three parameters are used to quantify tree effects, indicating the combined effects of daytime shading, nighttime radiation blockage, evapotranspirational cooling, and aerodynamic resistance on outdoor thermal conditions." Not quite sure whether air temperature alone can reflect all the aspects being mentioned here. Also, would including more indices in the assessment provide a more comprehensive understanding on the cooling efficiency?

Response: We have revised this sentence. The cooling efficacy of trees at the outdoor pedestrian level is represented by air temperature reduction, which has been used in many previous review studies. The indices for thermal comfort conditions are presented quantitatively in Figure 5, as discussed before.

Revision: Line 178-179

These three parameters are used to quantify the cooling efficacy of trees at the outdoor pedestrian level.

• For Figure-2, is there any extra information being provided by the graphic?

Response: We have improved the figure to show the interconnecting of the influencing factors and the cooling magnitude for case studies. Background climate, urban morphology, and tree traits are highly interconnected and collectively impact urban tree cooling effects in **Figure 5**.

Revision: Line 359-363

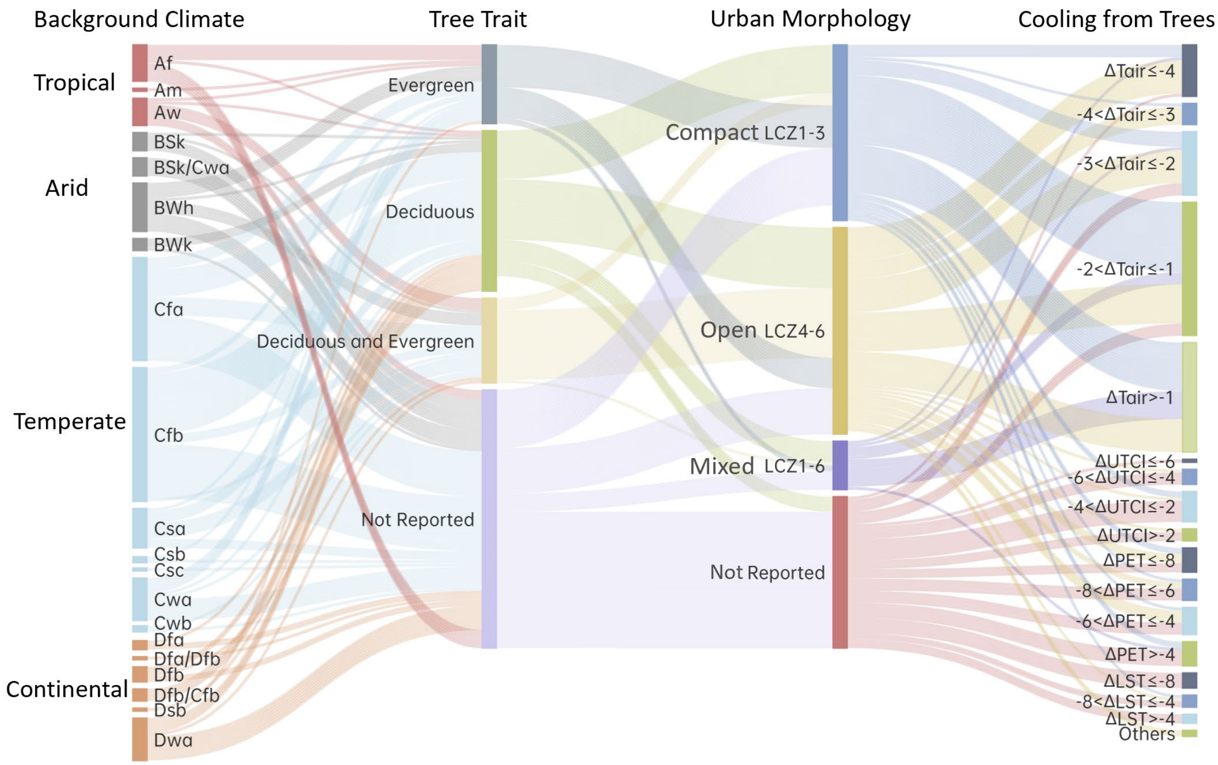

Figure 5. The hidden interconnections of background climate, tree traits, urban morphology characteristics, and the corresponding cooling potentials. The tree traits are characterized by leaf retention types and the urban morphology characteristics are characterized by local climate zone (LCZ). The cooling potential is evaluated using indicators including ΔT_{air}, ΔUTCI, ΔPET, and ΔLST.

• Maybe change the subheading "Quantification of the cooling potential in four background climates" to "Quantification of the cooling potential in tropical, arid, continental, and temperate climates" for consistency.

Response: We have changed to Quantification of tree cooling effects influenced by interconnected factors.

Revision: Line 343

Quantification of tree cooling effects influenced by interconnected factors

• For the section "Leveraging multiscale modeling to support urban planning", it is not very clear now how the development of multiscale models link to urban planning.

Revision: Line 526-531

Future research should leverage multi-variable analysis. Urban climates are influenced by a multitude of factors, including temperature, humidity, wind speed, solar radiation, and pollution levels[11,12]. Thermal comfort or thermo-physiological variables, such as UTCI and PET, are closely linked to heat-related health issues, particularly to quantify the risks for vulnerable populations such as older people, children, and those with pre-existing health conditions[11,13,14]. Utilizing multi-variable analysis is key to human-centered designs and interventions to enhance overall well-being.

Meanwhile, future research should also enhance modeling with multiscale studies, which allows for comprehensive understanding from micro- and local scale to mesoscale numerical modeling. Recently, more studies have been conducted at the meso-scale (**Supplementary. D**). Krayenhoff et al. revealed significant discrepancies in the results of mitigation strategies between micro-scale models and meso-scale models, which are caused by the disparity in simplification and assumption of the boundary conditions and physical calculations[63]. A few innovative studies have integrated methodologies combining simulations across different scales [24,64–67]. Compared with in situ measurements and numerical simulations, the use of remote sensing technology provides a cost-effective and non-invasive means of obtaining data on a large scale, allowing for more comprehensive assessments of the relationship between tree and urban thermal conditions[68]. Nevertheless, it’s important to note that remote sensing primarily captures data from the upper tree canopy, which may not fully represent the cooling effects provided by trees at ground or pedestrian level.

Reviewer #2 (Remarks to the Author): Review of "Harnessing cooling from urban trees: Interconnecting background climates, urban morphology, and tree traits"

The manuscript presents a review and meta-analysis of the cooling effect of trees, analyzing modulating factors such as urban morphology, background climate, and tree traits. This review is important as it brings together information that is otherwise available in other mini-reviews focused on different aspects of this topic. I recommend the acceptance of this manuscript following the address of the comments below:

Response to Reviewer #2: We would like to express our gratitude for taking the time to review our manuscript. Your constructive feedback and insights are much appreciated. Below, we provide detailed responses and outline the revisions made to the manuscript. The reviewer's comments are highlighted in **bold black**, and all revisions are highlighted in blue below and in the revised manuscript.

Major:

1. The introduction lacks sufficient details on greening-heat mitigation science. How does greenery cool our environment? A clue could be the leaf energy balance, and this could be interplayed with building (urban morphology) shading effects. A graphical description may be necessary.

Response: We appreciate your suggestion and have expanded this section to provide a clearer explanation and an illustration in the subplot to show how an urban tree cools our environment.

Revision: Line 48-67

Background climate[42,69,70], urban morphology[31,71,72], and tree traits[30,73] among other factors, function as interconnected factors and play complex roles that ultimately determine the cooling potential harnessed from urban trees (**Figure. 1**). Maximizing cooling from urban trees can be achieved by selecting optimal trees and strategically placing them, which requires a comprehensive understanding of the cooling mechanisms and these interconnected factors. Trees provide urban cooling in cities via several key mechanisms. During the day, trees provide shading by blocking shortwave solar radiation; their leaves perform evapotranspiration; and the foliage also modifies the surrounding airflow aerodynamically[20,55,60,61]. At night, spacious crowns of trees can trap longwave radiation from the ground surface[20,30,62]. Owing to the diurnal cycle of solar radiation and resultant leaf energy balance[60], the cooling effects of a tree typically follow a day-night pattern. Significant cooling primarily occurs in the afternoon, with minor cooling at night[21,74–77].

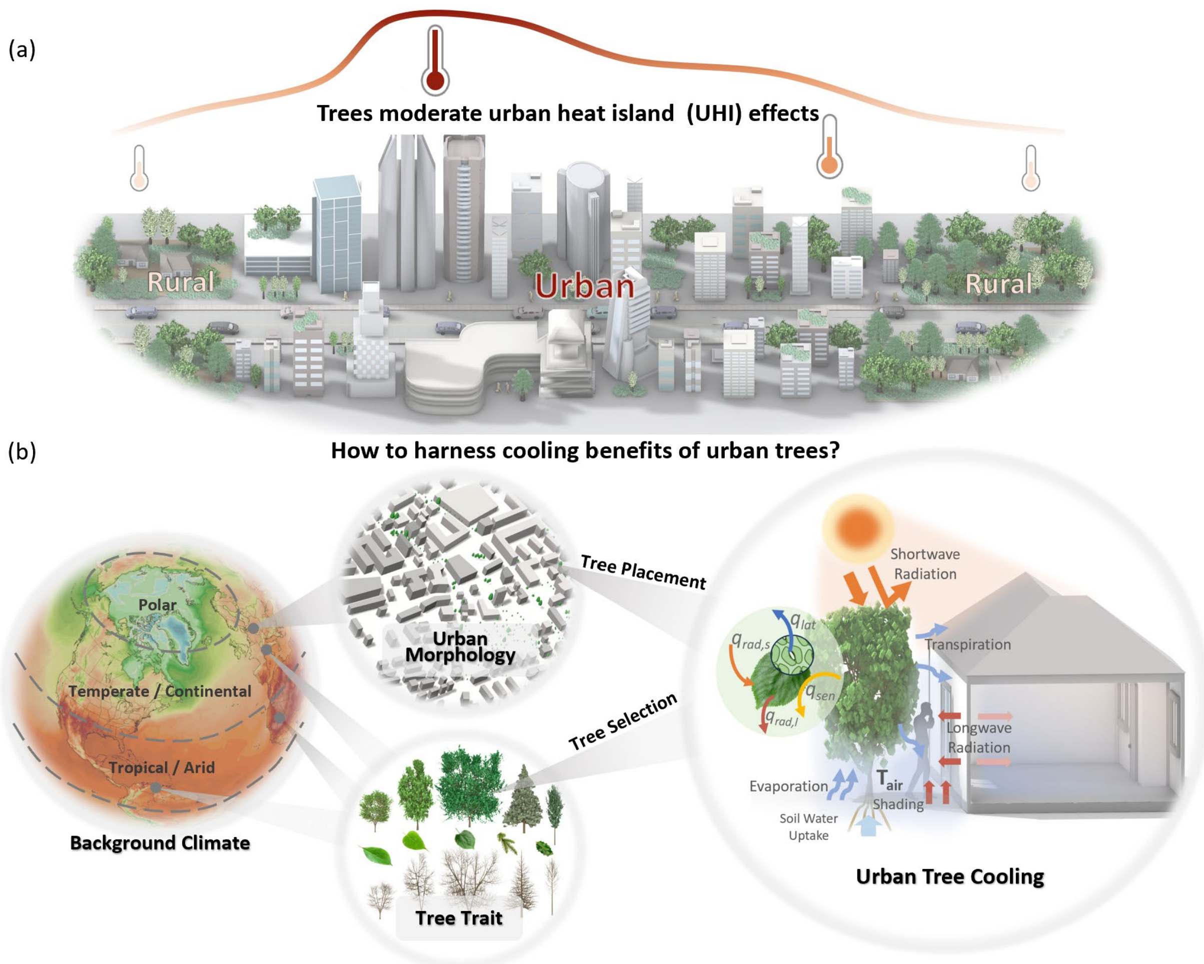

Figure 1. (a) Urban trees moderate urban warming caused by urban heat island (UHI) effects. (b) Interconnecting factors determine the cooling benefits of urban trees. Maximized cooling from urban trees is achieved by selecting the optimal trees and their placement, with an articulated understanding of the interconnecting elements: background climates, tree traits, and urban morphology. The cooling effect of urban trees is determined by a combination of mechanisms, such as shading (shortwave radiation blocking) and transpiration. On the leaf and its stomata scale, the leaf energy balance can be represented by $\boldsymbol{q}_{sen}$(sensible heat flux) + $\boldsymbol{q}_{lat}$(latent heat flux) = $\boldsymbol{q}_{rad,l}$(net longwave radiation) + $\boldsymbol{q}_{rad,s}$(net shortwave radiation).

2. A paragraph highlighting findings from some related reviews in the last few years would be appreciated and would reinforce the need for this review.

Response: To address this point, we have included a discussion in the introduction section to highlight critical related reviews. This addition emphasizes the current state of research in this area and underscores the need for our review.

Revision: Line 68-80

Past studies have explored the cooling effects of urban greenery[23,50,78–80], with the majority comparing various green and blue infrastructures[38,81–83]. Research has focused on specific climates or regions, such as temperate[83] or tropical climates[84], South Africa[78,80], and Asia[81]. Meta-analysis on tree traits has highlighted that tree canopy density significantly influences cooling benefits, with notable variations based on climate, tree size, ground surface cover, and leaf traits[30]. A recent systematic review exploring major types of blue and green infrastructures identifies botanical gardens, wetlands, green walls, street trees, and vegetated balconies as highly effective in moderating heat[82]. However, there is a notable gap in differentiating trees from other urban green infrastructures, especially considering trees' unique mechanisms, interactions with urban features, and substantial contributions to urban cooling. Another systematic review has pointed out a lack of quantification regarding the impact of local climate zones and land cover[23]. Although background climate[12,23,30,85], urban morphology[38,85,86], and tree traits[12,30,82,83] are frequently mentioned, they are often discussed in a fragmented manner without adequate quantification or synthesis related to cooling potentials. Thus, the global-scale understanding of the cooling benefit offered by urban trees is still not unequivocal.

3. I noticed that many important studies are missing from your pool. This might be linked to keywords used in the search. While "street tree" and "urban tree" were used on the greenery side, some studies may use other terms like "greening," "greenery," "vegetation" or just "trees". Similarly, on the thermal side, terms like "heat mitigation," "cooling effect," or "thermal benefit" should be included in the search. I demonstrated this by searching in sub-Saharan Africa and found interesting studies from the Federal University of Technology, Akure, Nigeria, which were not captured in the review. It's important to capture the minimal evidence from regions like this in a global review.

Response: Thank you for the kind suggestions. We have re-visited our search words for systematic review (**Figure A1**). Moreover, some studies are added, mostly concerning comparisons between trees and other types of cooling measures. In total, the revised systematic review includes 182 high-quality journal studies, with 126 case studies reporting quantitative changes in pedestrian-level air temperature due to urban trees.

Past review studies have explored the cooling effects of urban greenery[23,50,78–80], the majority comparing various green and blue infrastructures[38,81–83]. Previous reviews on this topic have mostly screened articles since year 2010 or after, with fewer than fifty urban tree research articles: 2012-2022 (76 UGI articles) [12], 2010-2019 (26 tree articles) [30], 2010-2023 (202 UGI including 20 tree articles) [82], 2010-2022 (72 UGI including 4 tree articles) [86], 2010-2019 (129 UGI including 12 tree articles) [84], 2010-2024 (218 UGI articles) [50], and 2015-2020 (79 UGI including 27 tree articles)[38].

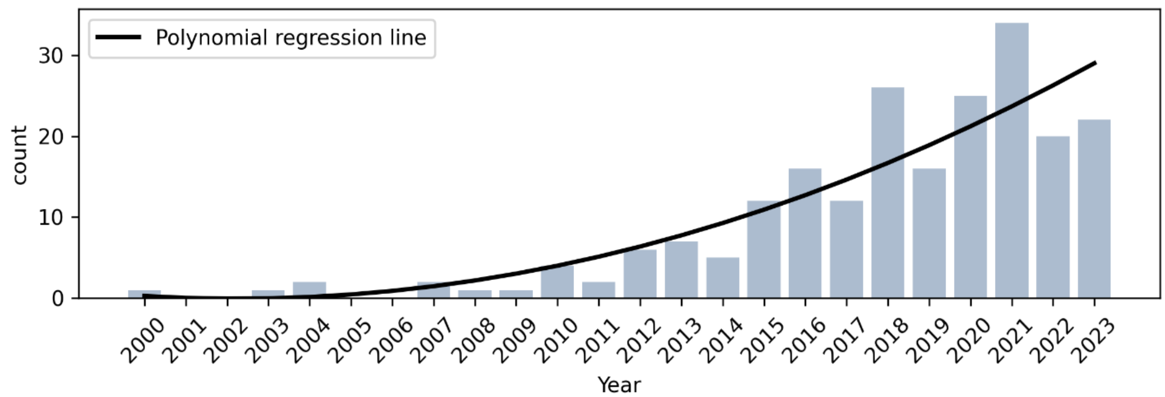

Figure R1. Number of urban tree cooling studies from 2000. These studies were selected using the same method with the PRISMA guidelines.

Figure R1 reflects an increasing trend in urban heat island research, with 95% of studies conducted post-2010. A comprehensive review has already summarized the heat mitigation studies with urban greening before 2010[1]. Considering the rapid changes in urban morphology and climate, including a 1.2°C increase in air temperature since the baseline period of 1951-1980, we decided to screen studies from 2010 to May 2023 to ensure a comparable context.

Revision: Line 108-126

Our systematic review provides a robust and transparent approach to summarizing the existing studies and results on the cooling effects of urban trees in outdoor environments. The study selection process of this review involves identifying relevant scientific papers published between 2010 and May 2023 in the Web of Science Core Collection and Scopus. One reason for this time frame is the dramatic increase in studies in this research field since 2010 (**Supplementary C Figure C**). Previous reviews in this area have typically examined fewer than 50 research articles from the year 2010 or 2015[12,30,38,50,79,82]. Additionally, given the rapid urbanization over the past decades, urban morphology and climate have altered significantly, which includes a 1.2°C increase in air temperature compared to the baseline period of 1951-1980[87]. This timeframe ensures a comparable context for the reviewed studies.

To achieve this, we used a combination of search terms, “urban” (“urban”, “street”, “neighbourhood”, “pedestrian” or “outdoor”) combined with “tree” (“tree”, “green”, “greenery”, “vegetation” or “nature-based solution”), and also combined with “cooling” (“cool”, “microclimate”, “thermal comfort”, “thermal benefit”, “heat island” or “heat mitigation”) to identify relevant studies on the cooling effects of urban trees in outdoor environments (**Figure A1**). The detailed steps in selecting literature following PRISMA guidelines, based on identification, screening, eligibility, and inclusion, are shown in **Supplementary A**. Our systematic review includes 182 high-quality journal studies, with 126 case studies reporting quantitative changes in pedestrian-level air temperature due to urban trees. Detailed documentation is listed in **Supplementary E**, where we describe the author (year), method, spatial scale, climate type, city or region, country, topic, and quantitative climate indicator.

Revision in Supplementary A.: Supplementary Information Line 3-17

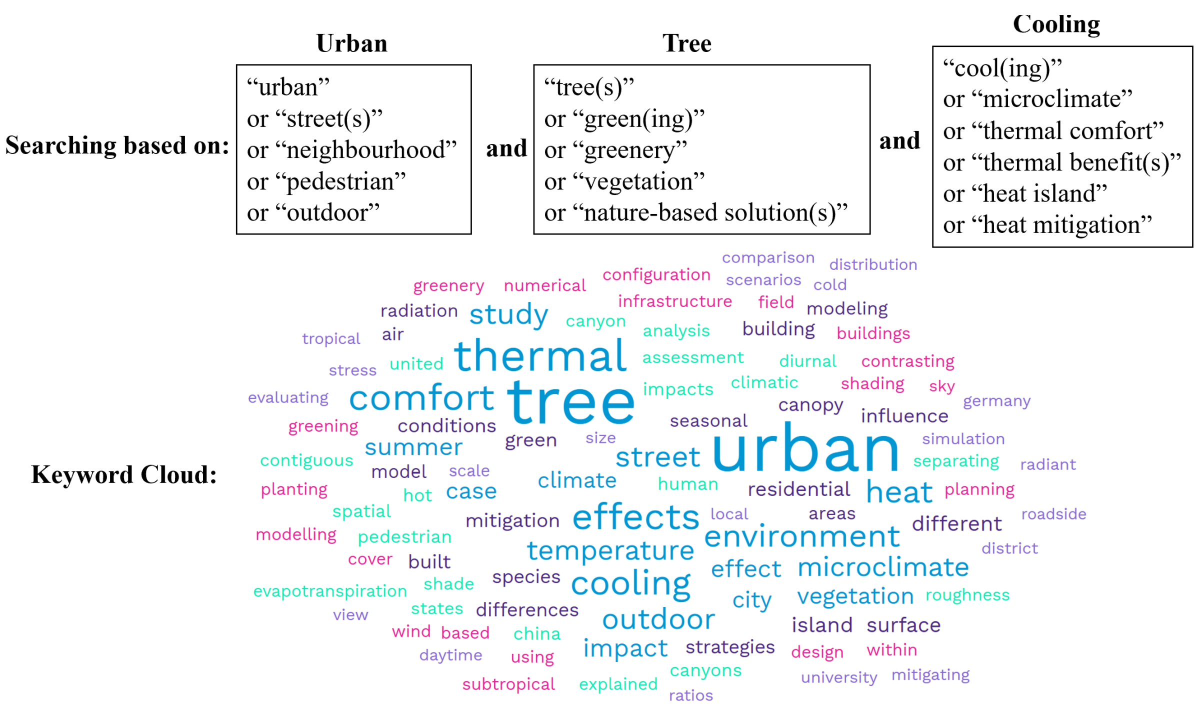

Figure A1. Illustration for keyword searching of systematic review. Word cloud is generated from the keywords from the eligible articles.

Following PRISMA guideline (**Figure A2**), in identification step, a total of 7859 articles are identified through the database. After that, 2517 records remain without duplications. In the second stage of the process, we screened the titles, abstracts, and keywords of the collected articles to exclude records that were not relevant to our research question. We excluded studies that focused on building energy consumption or green parks, for example. In total, 381 research articles are excluded during the screening process.

The third stage of the process involves assessing the full-text articles for eligibility based on the type of work and research scope. We excluded review papers and non-peer-reviewed studies from our analysis. 294 research articles are viewed and assessed in full text for eligibility.

In the final stage of the process, we carefully examined the research focus and methodology of the remaining articles and reviewed their cited references.

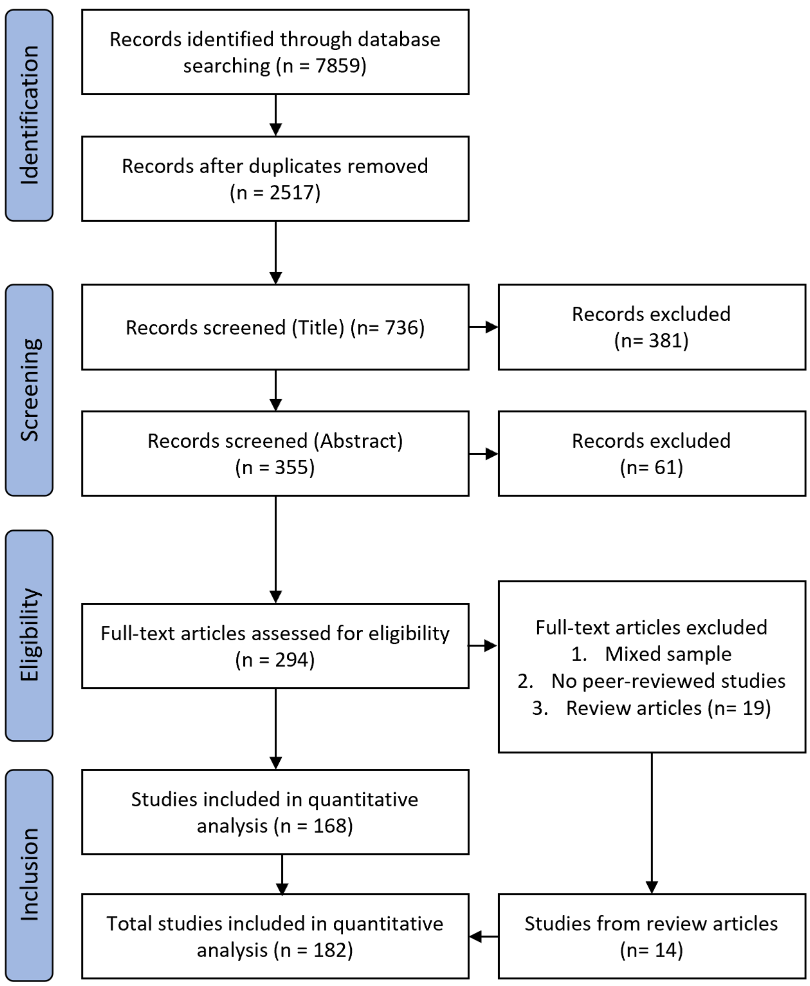

Figure A2. Identification, screening, eligibility and inclusion process of papers in review.

Minor:

1. Authors should clarify the rationale behind the selected study period.

Revision: Line 108-116

Our systematic review provides a robust and transparent approach to summarizing the existing studies and results on the cooling effects of urban trees in outdoor environments. The study selection process of this review involves identifying relevant scientific papers published between 2010 and May 2023 in the Web of Science Core Collection and Scopus. One reason for this time frame is the dramatic increase in studies in this research field since 2010 (**Supplementary C Figure C**). Previous reviews in this area have typically examined fewer than 50 research articles from the year 2010 or 2015[12,30,38,50,79,82]. Additionally, given the rapid urbanization over the past decades, urban morphology and climate have altered significantly, which includes a 1.2°C increase in air temperature compared to the baseline period of 1951-1980[87]. This timeframe ensures a comparable context for the reviewed studies.

2. Some grammatical checks are advised. For instance, in the abstract, "Stomata closer."

Response: Thank you for the suggestions. We have proofread the manuscript carefully to avoid grammatical mistakes.

3. There seems to be some inconsistency in the usage of certain terminology. For example, there were times when "tree trait" was used exclusively and inclusively of LAI/LAD. Additionally, tree-related indicators or factors in the Urban Morphology group across the study (see Figure 1) need clarification. How is "TD tree density" and "tree implementation" an urban morphology indicator?

Response: We have made a more straightforward definition of factors that relate to tree traits and urban morphology in the methods section. Factors that are more related to single-tree species or single-tree performances are classified as tree trait factors, such as LAI and LAD, tree morphology (TM), leaf morphology (LM), and leaf stomatal characteristics (LS). Factors that are more related to groups of trees or interactions with other urban features are classified as urban morphological factors, which include tree location and arrangement (TL), tree density (TD), tree implementation (TI), building morphology (BM), road orientation (RO), sky view factor (SVF), etc.

Revision: Line 135-157

Tree traits, by definition, refer to the characteristics of trees, such as their crown shapes, leaves, and roots. From our reviewed studies, factors that influence the cooling effects of trees include tree species (TS), tree morphology (TM), LAI and LAD (LD), leaf morphology (LM), and leaf stomatal characteristics (LS). Tree species, to a large extent, define most tree traits and are commonly reported in the reviewed studies. More than 120 plant species are reported in 57% of the reviewed studies, while over 40% do not specify the species (**Supplementary C**). For classification, we employ leaf retention type as an important tree trait parameter for quantitative analysis. Leaf retention type generally reflects leaf and crown shape, leaf texture, and seasonal leaf density (**Supplementary B**). Deciduous trees have broad, flat, thin, and flexible leaves that are up to 30 cm in length. Their crowns are usually rounded and spreading, with leaf density dramatically changing with the seasons. Evergreen trees have needle-like or scale-like leaves with a thick and waxy coating, usually small and narrow in size. Their crowns are typically conical (conifer), columnar, or irregular, with no seasonal changes in leaf density.

Urban morphology is the form, structure, and layout of urban areas, including the spatial patterns and physical configuration of buildings, streets, green and blue infrastructures, and open spaces. When it comes to urban tree cooling studies, topics mainly discussed include tree location and arrangement (TL), tree density (TD), tree implementation (TI), building morphology (BM), road orientation (RO), and sky view factor (SVF). To classify the urban morphological factors in the reviewed studies, we employ local climate zone (LCZ), a standard classification system describing different types of urban morphology[88]. Each LCZ type has unique thermal, aerodynamic, and radiative properties, influencing local air temperature, wind flow, and other climatic variables. We record LCZ for each case study based on the sky view factor, canyon aspect ratio, mean building height, and building surface fraction parameters, as described in **Supplementary B**. About 29% of studies are located in LCZ 1-3 compact areas, and 38% in LCZ 4-6 open areas (**Supplementary C**).

4. In the methods section, the statement about trees on exterior facades needs rethinking, as it may not be feasible.

Response: We have changed the statement about trees on "roof gardens and exterior facades" to "roof gardens, and other integrations with buildings."

Revision: Line 97-102

Urban trees have been utilized in various urban planning and landscape design applications, such as urban streets, roof gardens, and other integrations with buildings, residential areas, campuses, and urban parks [1]. In this study, to quantitatively assess their cooling effectiveness, we exclude research that solely focuses on trees planted in urban parks or integrated at rooftops, as in such locations, the impact of tree shading and evapotranspiration on pedestrian level is trivial or difficult to isolate.

5. The effect of tree shade on energy demand or usage seems to have been overlooked, which is a key sub-topic in the discussion, especially considering the emphasis on the built environment/"Urban."

Response: In the section future perspective for urban heat mitigation, we have extended the discussion and recommendations on quantifying global energy demand reduction and other tree cooling associated benefits.

Revision: Line 515-525

Apart from cooling benefits, urban trees offer other significant environmental advantages that support sustainable, resilient, and livable cities. Urban trees reduce energy consumption by lowering temperatures and providing shade during summer, thereby decreasing the need for air conditioning in adjacent buildings[89]. In tropical and arid climates, evergreen trees provide continuous cooling, reducing energy demand year-round[89,90]. In temperate and continental climates, deciduous trees are favorable for reducing energy demand because they shed leaves in winter, thus minimizing summer cooling demand and allowing for necessary winter solar access. This overall reduction in energy demand not only leads to cost savings for individuals but also benefits urban power grids during peak usage periods. Additionally, urban trees can enhance air quality by filtering pollutants, which reduces the urban heat accumulation from air pollution[16,91]. Trees can also reduce the incidence of heat-related illnesses and fatalities. Future research should further explore the various benefits of urban trees in urban environments.

6. It would be valuable to discuss how heatwaves impact the cooling efficiency of trees and whether any studies quantify this effect.

Response: Thank you for the suggestion. The heatwave impacts on the cooling efficiency of trees is important; therefore, we extend the discussion on it in selecting appropriate species to ensure they suit the current and future warmer climates.

Revision: Line 445-472

Urban trees for heat mitigation in a warming climate

As one of the key factors in the integrated approach, background climates are essential to the cooling effects of urban trees [41,42], which regulate the cooling efficacy and influence the selection of appropriate species.

Embedding climatic factors in urban planning and tailoring tree-planting strategies is crucial, especially in the face of global warming.

Our meta-analysis illustrates the significance of background temperature and precipitation on the cooling effects of trees in tropical climates [43]. Cities in arid and tropical climates, generally located at lower latitudes, are subject to intense solar irradiance and high background air temperatures[21,44]. Our findings align with those of Yang et al.[45] and Su et al.[46], demonstrating that the cooling efficacy of trees varies markedly among cities, with higher values attained in hot and dry cities. Given that the vapor pressure within the stomata is near the saturation vapor pressure at the leaf temperature, the potential for transpirational cooling in hot climates is significant and, meanwhile, highly sensitive to environmental humidity levels. Wang et al.[47] conducted meso-scale numerical simulations and compared the near-surface temperature with/without trees across the contiguous United States. Among the six regions, it was found that regions in temperate oceanic climate have relatively lower cooling potential than other climate types.

Given current global warming and increasing precipitation, it is becoming increasingly imperative to reform urban planning policies to embed climate-specific strategies and adapt to future warming. Urban planners should consider choosing resilient species that can thrive in changing climate conditions. Heatwaves can strain trees by increasing their water demand while simultaneously reducing water availability due to higher evapotranspiration rates. Exceptionally high temperatures and extremely high vapor pressure deficits at the hottest hours can cause stomatal closure, which reduces transpirational cooling [21,48,49], particularly in tropical and arid climates. Studies have quantified that during heatwaves, the cooling benefits of urban trees could decrease by up to 30% due to stress-induced stomatal closure and water scarcity[50,51]. This reduction in transpiration can significantly affect the microclimate benefits provided by urban forests, making cities more vulnerable to heat stress. Additionally, prolonged heat stress can lead to tree mortality, further diminishing urban canopy cover and exacerbating the heat island effect. This phenomenon highly depends on tree species. Urban planners should plan for future warmer climates by choosing resilient species, such as anisohydric species, that can thrive in changing climate conditions[52].

7. Summarizing the measurement and modeling techniques/methodology/tools and expressing thoughts on these techniques may be useful, perhaps in the supplementary information.

Response: Thank you for the suggestion. We have elaborated the discussion on recent advances in methodologies in the research articles in **Supplementary D**.

Revision Supplementary D: Supplementary Information Line 83-109

Supplementary D. Research methodologies of the reviewed literature

Numerical simulation, full-scale and reduced-scale measurement, and remote sensing are the common, extensively applied methodologies for studying the thermal comfort of outdoor environments[92]. About 90% of the reviewed studies, focusing on street trees or trees adjacent to buildings, are carried out based on measurement and simulation methods. The choice of methodology depends on the research scales and available resources of the studies.

Studies on the local scale and micro-scale (up to 2 km) take up more than 80% of the studies. Micro-scale studies refer to a single street canyon or idealized standard street canyon investigations, while local scale studies investigate a neighborhood area with realistic urban morphology. At the micro- and local scale, the shading, evapotranspiration, and aerodynamic influences are investigated with high resolution, using field measurement, wind tunnel measurement, and urban microclimate simulations. On the micro-scale and local scale, Computational Fluid Dynamics (CFD) simulation is often used to predict complex outdoor wind and thermal environments under urban microclimate boundary conditions. More specifically, most of the simulation is coupled with heat-air-moisture (HAM) transfer model using software, including ENVI-met [93,94], OpenFoam [60,95], Anasys Fluent [96], RayMan [15,97], and SOLWEIG [98,99]. A few measurement studies are conducted on a reduced scale, in outdoor settings [100] and in the wind tunnel [20]. Urban trees are typically modeled as a porous medium with defined drag coefficients, thermal properties, and minimal stomatal resistance[60,67]. The CFD model can be solved in coupled subdomains, consisting of radiation, air, solid, and vegetation subdomains[60]. Radiation models, such as urban canopy models, are developed to simulate radiative heat exchange between trees and surrounding urban canopies[101–104].

The meso-scale studies account for around 10% of the total reviewed studies, mostly using Mesoscale Meteorological Models (MMMs) [105,106] and remote sensing technologies [107,108]. Weather Research and Forecasting (WRF) and Consortium for Small-scale Modeling (COSMO) are meso-scale systems widely used in weather forecasting and urban climate research. They can be coupled with small-scale models to increase the resolution of the simulation [92]. Remote sensing and GIS-based assessment can be used to understand different tree types, LST, humidity levels, etc. As satellite technology advances, the remote sensing technique is anticipated to become an increasingly helpful, non-invasive tool for collecting data.

8. On page 9, "urban greenery" was first used, which implies not just trees. Consider revising to "tree" or stating the definition of urban greening.

Response: Thank you for the suggestions. We have replaced "urban greenery" with "urban trees".

Revision: 222-223

In terms of the influence of background humidity levels, the cooling efficacy of urban trees is highest in hot and dry cities where transpirational cooling is enhanced due to a high vapor pressure deficit[45].

9. On page 10, it was mentioned that "...planned vegetation can exacerbate thermal discomfort issues in humid tropical cities." Is there only one study that addresses this, and can this statement be expressed in quantitative terms?

Revision: Line 235-238

Excessively planted trees or trees planted in enclosed spaces with a humid climate can result in low cooling efficacy or even thermal discomfort, increasing PET by up to 2°C under high humidity and stagnant air conditions [84,109–111]. Effective urban design requires lowering the SVF to an appropriate value to allow for adequate air ventilation.

10. On page 11, "must be thoughtfully designed" is mentioned. Can tree species be designed?

Revision: Line 252-253

Proper selection of tree species can enhance the cooling benefits by maximizing shading and transpirational cooling while also improving pedestrian comfort via natural windbreaks.

11. On page 12, "...84 studies" were mentioned, not 131.

Response: We have revised and clarified the manuscript to ensure the consistency of the 182 articles in the systematic review and 126 case studies (reported air temperature reduction) for most of the meta-analysis.

Reviewer #3 (Remarks to the Author): The manuscript provides an original and valuable overview of the growing body of literature on the topic of local climate regulation by urban trees. Due to the high relevance of the topic, a systematic review of the existing evidence, as the one provided by the Authors, is urgently needed. However, there are some aspects of the manuscript that need to be addressed.

Response to Reviewer #3: Thank you for reviewing our manuscript. Your valuable comments and feedback have helped us greatly improve its quality. In this letter, we address each of your concerns in a point-by-point manner. The reviewer's comments are highlighted in **bold black**, and all revisions are highlighted in blue below and in the revised manuscript.

General comments:

The structure of the paper should be revisited to make the content clearer, following the usual manuscript's structure consisting of introduction, methods, results, discussions and conclusion. This would help to simplify the content and avoiding some redundancy in the illustration of the results.

Response: Thank you for the comment on the structure. We have revisited the manuscript and restructured it. The current structure largely follows the structure of the review articles in the journal Communications Earth & Environment. The introduction and methods introduce the aim, scope, and research questions for this review article. For the section "Factors influencing urban tree cooling efficacy", "Interconnections between climate, urban morphology, and tree traits" and "Guiding principles for harnessing cooling effects of urban trees", we provide several sentences outlining the contents under each heading. The discussion is covered by a section on guiding principles with policy implications and a section on limitations and future perspectives. The conclusion then summarizes the main findings and emphasizes the importance of this study. In addition, we have added a description of the structure to facilitate readers.

Revision: Line 81-90

In this review, we offer a comprehensive global assessment of tree-related cooling effects reported in 182 journal articles since 2010, with a meta-analysis of the data presented in these studies. We begin by introducing the background and motivation of the study. The methods section outlines the systematic review and meta-analysis approach, explaining the selection criteria and the metrics used to evaluate cooling effects. After that, we discuss core findings for the impacts of background climate, urban morphology, and tree traits. Subsequently, we present a meta-analysis of the reported data with quantitative analyses to show the interconnections between influencing factors. This is followed by the guiding principles section, which elaborates on the results and provides strategic, integrated recommendations for urban planners and policymakers. Finally, the article discusses the limitations and future perspectives and concludes by summarizing the research findings.

Specific comments:

- The numbering of the lines is missing: I recommend to add the numbering for the second round of review.

Response: We have now added the line numbering for the second round of review.

- Proofreading of minor punctuation and text inconsistencies is recommended

Response: Thank you for the suggestions. We have proofread the revised manuscript carefully.

- page 15: it is not clear what the authors mean with absolute and relative temperature reduction. A definition of the terms is needed

Response: We have clarified the absolute and relative temperature reduction in the revised manuscript.

Revision: Line 331-342

Studies on the micro and local scales (up to 2 km) take up more than 80% of the studies, as summarized in **Supplementary C**. **Figure 4** highlights the estimated urban tree cooling potential based on micro and local scale studies. In particular, we report cooling benefits ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) in each city. After the implementation of trees, in 83% of cities, the air temperature of the hottest month was reduced to below 26 °C, meeting the thermal comfort threshold[25].

When comparing absolute temperature reduction (ΔT_{air}) and relative temperature reduction ($\Delta T_{air}/T_{air}$), trees in tropical and arid climates demonstrate more significant cooling effects in absolute terms, while trees in continental and temperate climates offer a higher relative air temperature reduction. In other words, the proportional reduction of air temperature by trees in continental and temperate climates is more pronounced. Therefore, future urban planning initiatives should consider both the relative and absolute impacts of trees' cooling potential concerning local background climates. This approach will enable the implementation of targeted strategies that maximize the cooling potential of trees in respective climates.

- Figure 6: what do the "cont'd" and black arrows mean in the graph? It is also not clear what the Authors mean with "Tair,tree is approximated by Tair and historically observed cooling capabilities of trees in respective cities".

Response: We have revised the sentence and clarified the definition. We have removed the "cont'd" and black arrows to avoid confusion.

Revision: Line 323-330

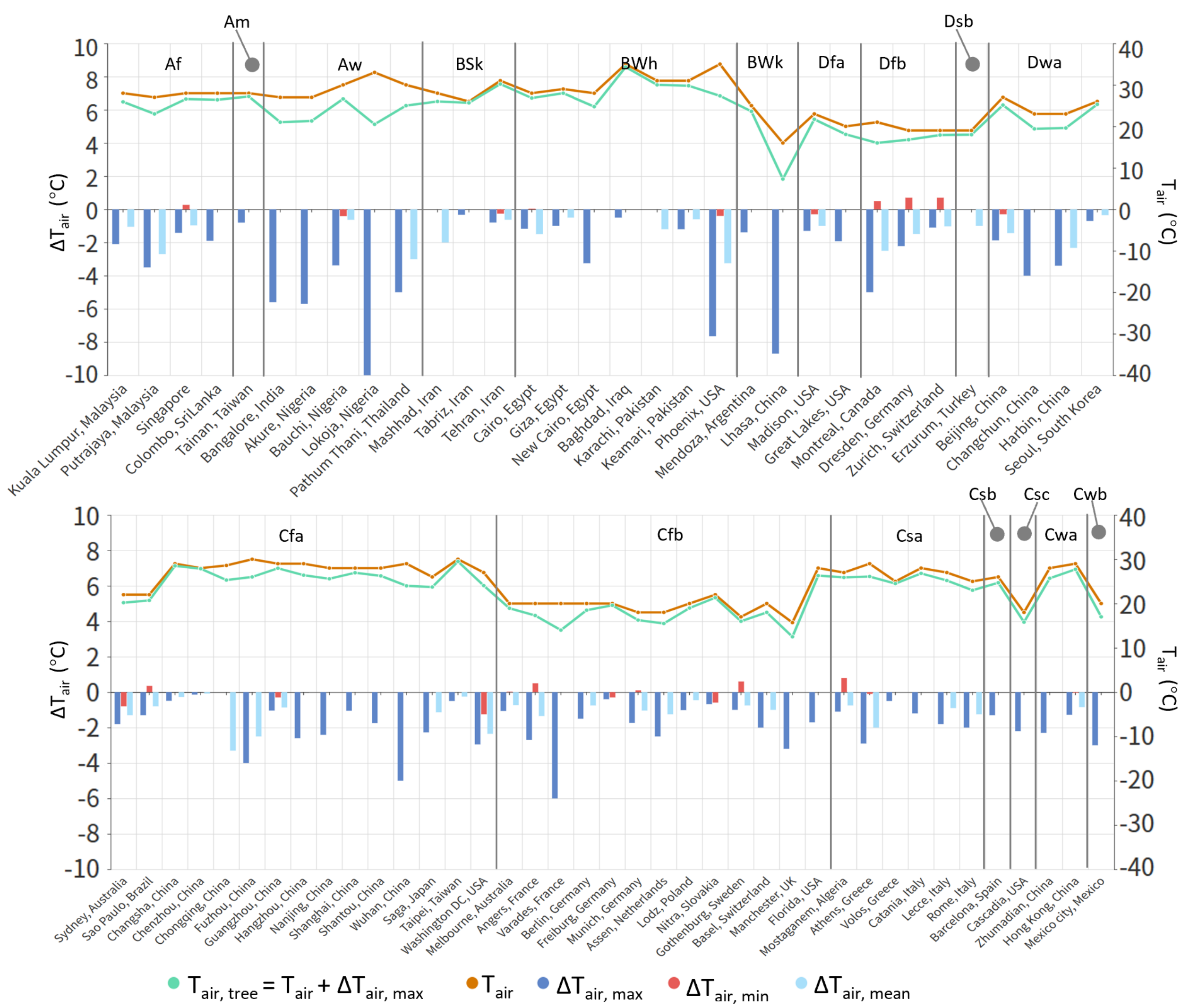

Figure 4. Estimated urban tree cooling potential in 71 major cities or regions. Solid lines compare the achievable air temperature with urban trees ($T_{air,tree}$, green line referring to the right axis) vs. the historically hottest month air temperature observed in the reviewed studies (T_{air}, orange line referring to the right axis). $T_{air,tree}$ represents a lower air temperature cooled by trees, which equals the sum of the historically hottest month air temperature observed (T_{air}) and achievable air temperature reductions ($\Delta T_{air,max}$, blue bar referring to the left axis). Bars in dark blue, red, and light blue represent the reported cooling benefits characterized by $\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively.

- Figure 7 (caption): perhaps it is redundant to add information on what the boxplots represent (e.g. that top and bottom limits of boxplots are the 25th and 75th percentile and that dots represent outliers).

Response: This is required by the journal Communications Earth & Environment. We have reduced the redundant description, and it is more concise.

Revision: Line 386-392

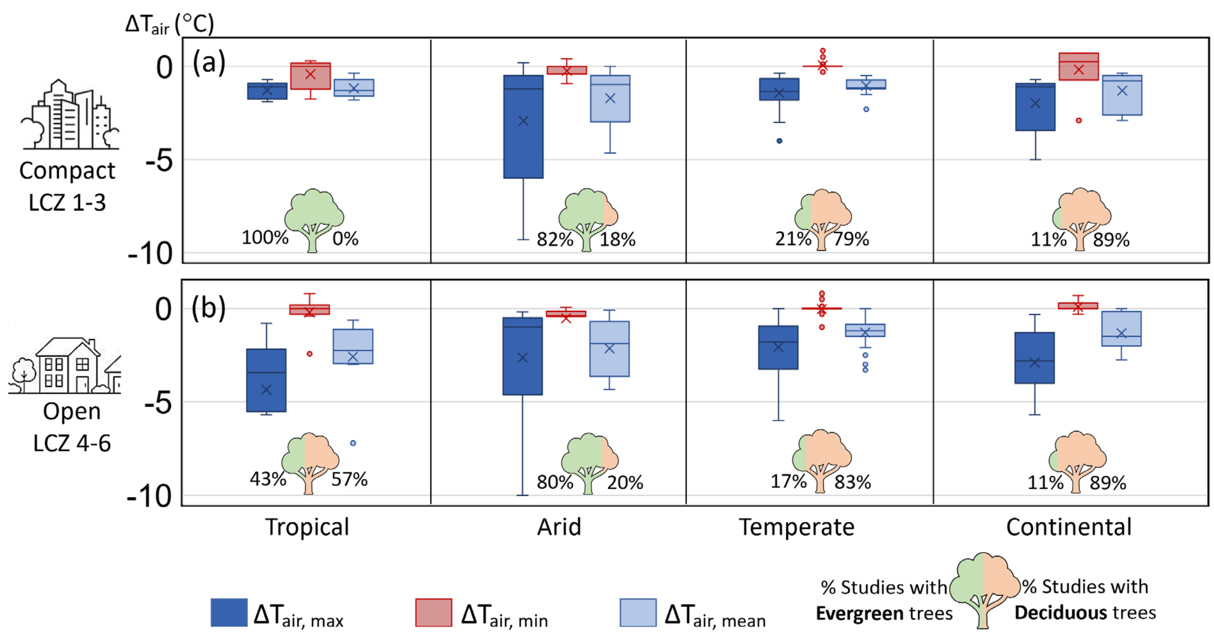

Figure 6. The cooling potential of urban trees evaluated across complex dimensions. The box plots display maximum ($\Delta T_{air,max}$, dark blue), minimum ($\Delta T_{air,min}$, red), and mean ($\Delta T_{air,mean}$, light blue) air temperature reductions and the use of evergreen and deciduous trees, for compact and open urban morphology as well

as in tropical, arid, temperate, and continental climates. The box plot's rectangle covers the interquartile range (25th to 75th percentiles). Inside, lines mark the median, and a cross marks the mean. Whiskers extend to the data's minimum and maximum within 1.5 times the interquartile range.

- While the contribution of background climate is exhaustively represented in the manuscript with figures and tables, a schematic representation of the other factors influencing the cooling is lacking. A table or graph sumamrizing the effect of tree traits and urban morphology could be useful.

Response: Thank you for the suggestions. We have extended and elaborated on the urban tree cooling mechanisms in a subplot in **Figure 1**.

Revision: Line 48-56

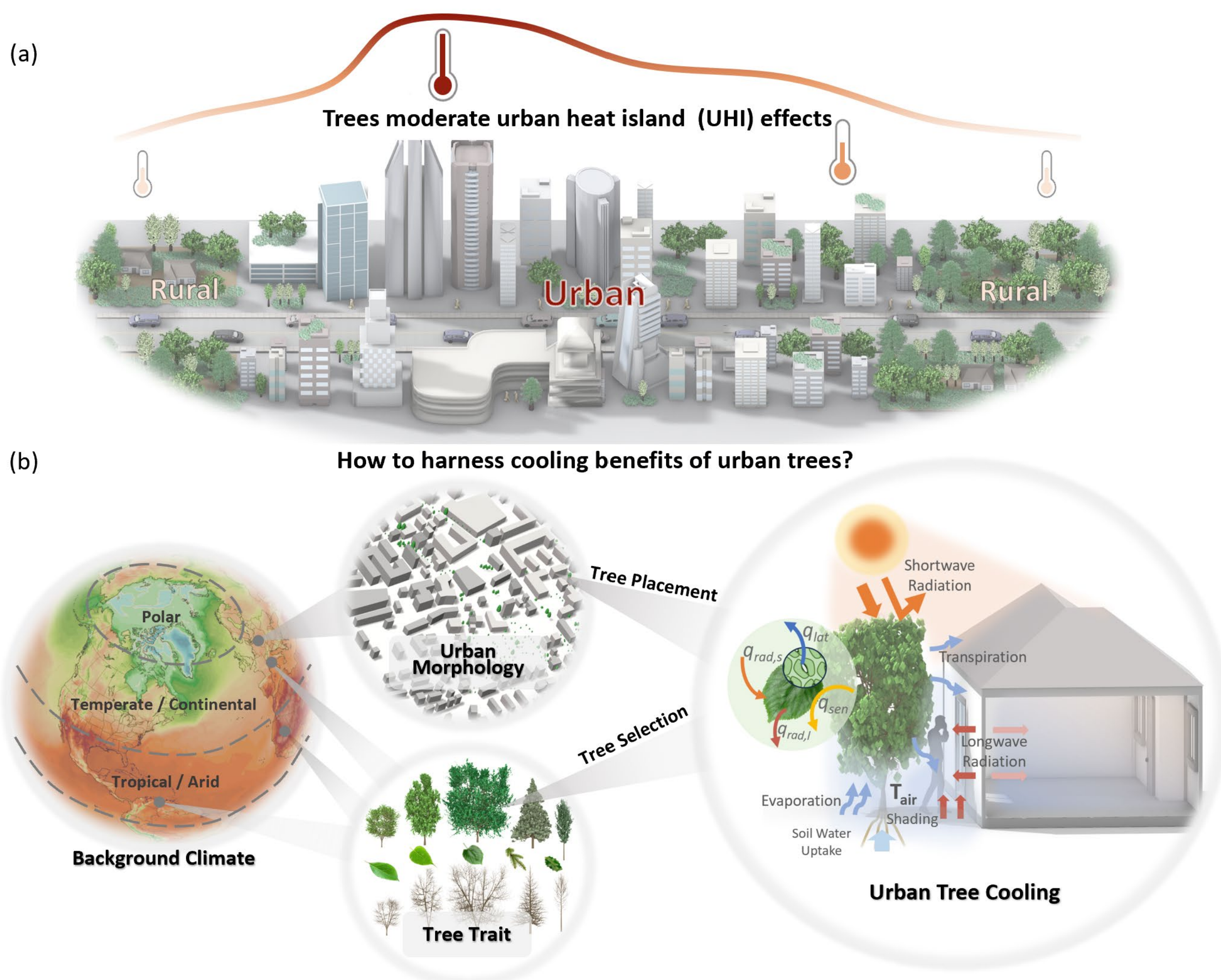

Figure 1. (a) Urban trees moderate urban warming caused by urban heat island (UHI) effects. (b) Interconnecting factors determine the cooling benefits of urban trees. Maximized cooling from urban trees is achieved by selecting the optimal trees and their placement, with an articulated understanding of the interconnecting elements: background climates, tree traits, and urban morphology. The cooling effect of urban trees is determined by a combination of mechanisms, such as shading (shortwave radiation blocking) and transpiration. On the leaf and its stomata scale, the leaf energy balance can be represented by $\boldsymbol{q}_{sen}$(sensible heat flux) + $\boldsymbol{q}_{lat}$(latent heat flux) = $\boldsymbol{q}_{rad,l}$(net longwave radiation) + $\boldsymbol{q}_{rad,s}$(net shortwave radiation).

Reviewer #4 (Remarks to the Author): I'm excited to review this manuscript since such a topic is very important for urban and urban dwellers. The author summarized recent studies to investigate the effects of urban morphology, tree traits, and climatic background on the cooling effect of urban trees. This is a significant improvement for current research since it would be a comprehensive analysis, which is critical for urban planning and management. Nevertheless, I think there are still some serious issues.

Response to Reviewer #4: We sincerely appreciate your feedback on our manuscript. In response to your comments, we made substantial revisions to improve the manuscript by extending our discussion and quantifications for a more comprehensive analysis. The reviewer's comments are highlighted in **bold black**, and all revisions are highlighted in blue below and in the revised manuscript.

1) The sample size of only 85 papers, in my opinion, is too small for the author to do review this scientific subject, even though the author highlights some important and intriguing points. It appeared that the author has largely concentrated on the impact of climatic backgrounds. However, I find the current summary so deficient in terms of urban morphology and tree traits that it is hard for me to draw some conclusions. Although the author has summarized a few publications, these have mainly consisted of a list of findings from one or two of the articles. Can these on their own represent the findings of the current research? I'm concerned about it. For example, the author highlights how tree traits affected the cooling effect. What are the outcomes? Its cooling impact can be increased by raising LAI and LAD. Even if this is a generally acknowledged conclusion, is it unquestionable? What are the new findings of this study based on the knowledge that already exists?

Response: We employed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[112], which is a popularly used comprehensive method synthesizing the existing studies on a particularly narrowed topic, providing an objective and rigorous analysis of the available evidence. We have re-visited our search words for systematic review (**Figure A1**). Moreover, some studies are added, mostly concerning comparisons between trees and other types of cooling measures. In total, the revised systematic review includes 182 high-quality journal studies, with 126 case studies reporting quantitative changes in pedestrian-level air temperature due to urban trees. Although most of the quantitative analyses were conducted with 126 case studies, we also tried to quantitatively understand a total of 182 articles with many more indicators, such as UTCI, PET, and LST (**Figure 5**).

Past review studies have explored the cooling effects of urban greenery[23,50,78–80], the majority comparing various green and blue infrastructures[38,81–83]. Previous reviews on this topic have mostly screened articles since year 2010 or after, with fewer than fifty urban tree research articles: 2012-2022 (76 UGI articles) [12], 2010-2019 (26 tree articles) [30], 2010-2023 (202 UGI including 20 tree articles) [82], 2010-2022 (72 UGI including 4 tree articles) [86], 2010-2019 (129 UGI including 12 tree articles) [84], 2010-2024 (218 UGI articles) [50], and 2015-2020 (79 UGI including 27 tree articles)[38].

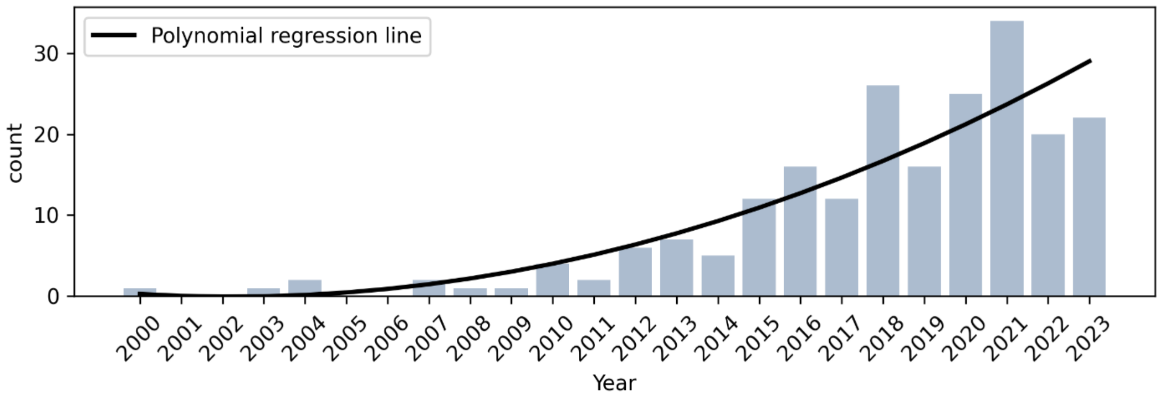

Figure R1. Number of urban tree cooling studies from 2000. These studies were selected using the same method with the PRISMA guidelines.

Figure R1 reflects an increasing trend in urban heat island research, with 95% of studies conducted post-2010. A comprehensive review has already summarized the heat mitigation studies with urban greening before 2010[1]. Considering the rapid changes in urban morphology and climate, including a 1.2°C increase in air temperature since the baseline period of 1951-1980, we decided to screen studies from 2010 to May 2023 to ensure a comparable context.

In addition, we have re-visited all 182 articles to quantify the tree trait and urban morphological factors in each study. We recorded LCZ for each case study based on the sky view factor, canyon aspect ratio, mean building height, and building surface fraction parameters described. Moreover, more than 120 plant species are reported in these case studies. For classification, we employ leaf retention type as an important tree trait parameter for quantitative analysis. The leaf retention type can generally reflect its leaf and crown shape, leaf texture, and seasonal leaf density.

The manuscript is re-structured. “Factors influencing urban tree cooling efficacy” presents three key aspects that are frequently investigated in the reviewed articles, with key findings presented. “Interconnections between climate, urban morphology, and tree traits” presents a comprehensive understanding with a quantitative meta-analysis of interconnected factors that collectively determine the cooling benefits of urban trees. “Guiding principles for harnessing cooling effects of urban trees” presents the integrated approach to align key practices, such as tree selection and tree placement, with urban morphology and background climate. We further elaborate on tree planning strategies for the future warming climate.

Revision: Line 108-126

Our systematic review provides a robust and transparent approach to summarizing the existing studies and results on the cooling effects of urban trees in outdoor environments. The study selection process of this review involves identifying relevant scientific papers published between 2010 and May 2023 in the Web of Science Core Collection and Scopus. One reason for this time frame is the dramatic increase in studies in this research field since 2010 (**Supplementary C Figure C**). Previous reviews in this area have typically examined fewer than 50 research articles from the year 2010 or 2015[12,30,38,50,79,82]. Additionally, given the rapid urbanization over the past decades, urban morphology and climate have altered significantly, which includes a 1.2°C increase in air temperature compared to the baseline period of 1951-1980[87]. This timeframe ensures a comparable context for the reviewed studies.

To achieve this, we used a combination of search terms, "urban" ("urban", "street", "neighbourhood", "pedestrian" or "outdoor") combined with "tree" ("tree", "green", "greenery", "vegetation" or "nature-based solution"), and also combined with "cooling" ("cool", "microclimate", "thermal comfort", "thermal benefit", "heat island" or "heat mitigation") to identify relevant studies on the cooling effects of urban trees in outdoor environments (**Figure A1**). The detailed steps in selecting literature following PRISMA guidelines, based on identification, screening, eligibility, and inclusion, are shown in **Supplementary A**. Our systematic review includes 182 high-quality journal studies, with 126 case studies reporting quantitative changes in pedestrian-level air temperature due to urban trees. Detailed documentation is listed in **Supplementary E**, where we describe the author (year), method, spatial scale, climate type, city or region, country, topic, and quantitative climate indicator.

Revision in Supplementary A.: Supplementary Information Line 3-5

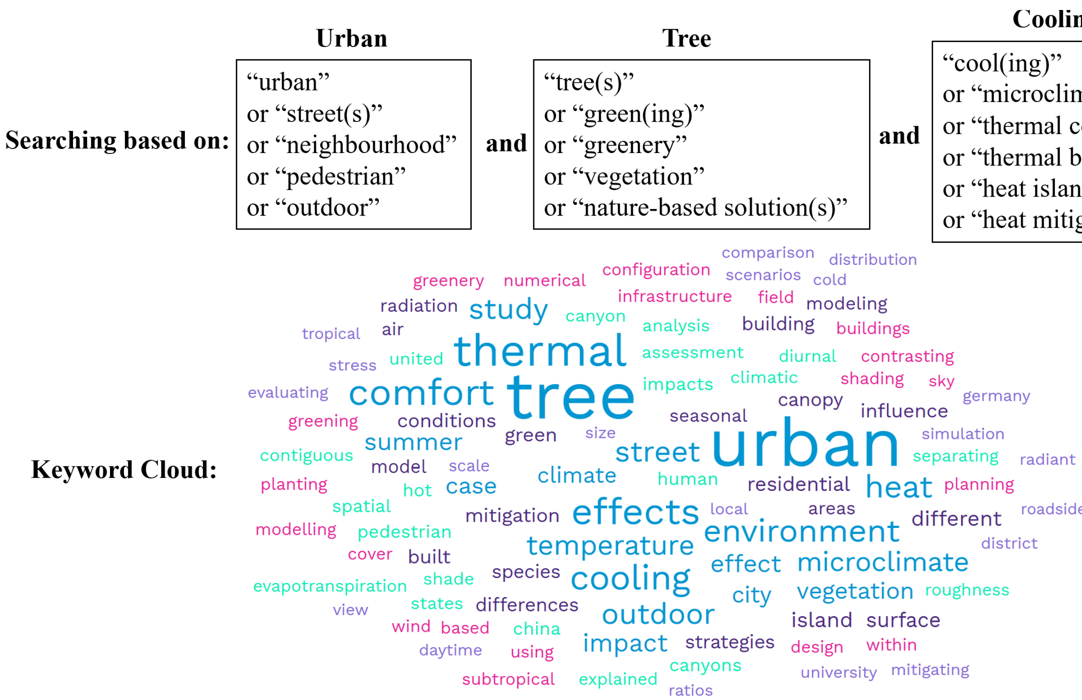

Figure A1. Illustration for keyword searching of systematic review. Word cloud is generated from the keywords from the eligible articles.

2) Furthermore, I cannot find any pertinent conclusions in "internecting the climate background, tree traits, and urban morphology". Except for the results of a few publications, the author only touched on this very briefly in the guiding principles section; there was no real reviewing, that is no conclusions offered. The author may consider conducting a review based only on climate background, which is also an aspect that is currently being discussed more. In this case, the topic will be more focused, and I believe it can be further analyzed in depth.

Response: We have extended our discussion and more in-depth review of these interactions and provided clearer conclusions on the interconnection of the climate background, tree traits, and urban morphology.

Revision: Line 270-396

Interconnections between climate, urban morphology, and tree traits

Most research focuses on case studies in specific study sites with distinct local climates. Consequently, there is a notable gap in systematically studying the integration of background climates, tree traits, and urban morphology factors. This section aims to provide a comprehensive understanding through a quantitative meta-analysis of interconnected factors that collectively determine the cooling benefits of urban trees.

Diurnal cooling effects in tropical, arid, continental, and temperate climates

We synthesize the key case studies for meta-analysis in **Figure 3**. The cooling effects of trees in these studies are quantitatively analyzed in terms of $\Delta T_{air,max}$ and $\Delta T_{air,mean}$ across different climates, spatial scales (micro, local, and meso), and methods (measurement and simulation). Selected factors are also summarized in **Figure 3**, including leaf retention type as a tree trait and local climate zone (LCZ) as an urban morphology characteristic.

Figure 3 demonstrates that the reviewed studies encompass a wide range of urban morphology types and a diverse variety of tree types across different climates. For tropical climates, observed daily maximum temperature change $\Delta T_{air,max}$ varies between -12 °C (cooling) and +0.8 °C (warming). Specifically, the maximum daytime cooling effects of trees can reach up to -5°C in Thailand[15], -5.6°C in India[16], and -12°C in Nigeria[17], in Aw climate. However, in tropical rainforest climates (Af), where humidity is higher, the cooling effect drops to approximately a mean value of -2 °C. The cooling potential of urban trees in arid climates is also significant, with observed $\Delta T_{air,max}$ reaching up to -9.3 °C (cooling), as shown in **Figure 3**. It is worth noting that a minor warming effect (+0.4 °C) can occur during the nighttime in these arid climates. In continental climates, the cooling potential can reach up to -5.7 °C (**Figure 3**), although nighttime warming effects are frequently reported in Dfb (humid continental) climates [18,19]. In temperate climates, the range of observed ΔT_{air} varies from -6.00 °C (cooling) to +1.50 °C (warming).

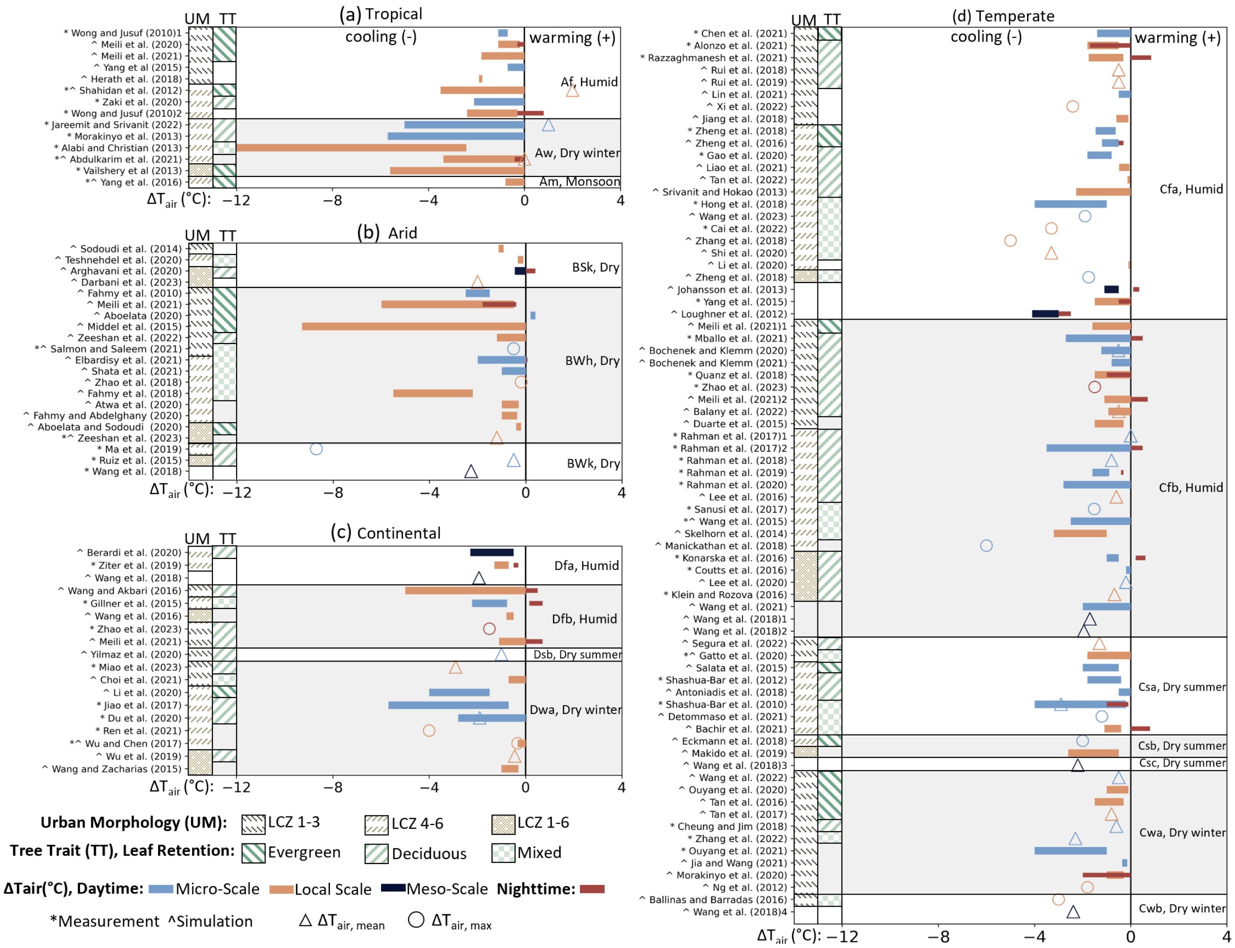

Figure 3. Diurnal variation of ΔT_{air} observed in the (a) tropical, (b) arid, and (c) continental climates. The plotted bars and markers (triangle/circle) represent the cooling or warming efficacy, and the shades in blue, orange and black colors represent the spatial scales on which the cooling or warming was observed. The nighttime effects caused by trees are presented in red. The studies are also classified based on urban morphology (represented by LCZ), tree traits (represented by leaf retention types), and methodologies (measurement or simulation).

The precipitation difference among the sub-climate types affects the cooling of trees. On average, tropical wet climates (Aw) exhibit more significant cooling benefits from trees compared to tropical rainforest climates (Af). This is due to the higher year-round humidity levels in Af. The $\Delta T_{air,max}$ difference between dry (Aw) and humid (Af) climates is as significant as 2.12 °C. However, in temperate climates, the $\Delta T_{air,max}$ difference between dry (Csa and Csb) and humid (Cfa, Cfb, Cwa, and Cwb) climates is negligible, at only 0.28 °C.

Studies show that a higher diversity of plant use, particularly the mixed use of various sizes of evergreen and deciduous trees, is linked to open urban forms (LCZ 4-6), often resulting in more significant cooling in tropical, temperate, and continental climates. The combined use of deciduous and evergreen trees generally results in 0.5°C higher cooling compared to studies using only deciduous or evergreen trees in these climates. In arid climates, studies with solely evergreen trees show higher tree cooling potential.

These studies provide convincing evidence that the cooling benefits of trees during the daytime are significant in tropical, arid, and continental climates. However, minor warming effects can be observed in some cases during the nighttime in continental climates. The reduction in cooling or minor warming effects during the nighttime can be caused by stomatal closure, reduced heat removal due to aerodynamic resistance, and the trapping of longwave radiation beneath the tree canopy[20,21].

Results in different spatial scales with different methods may exhibit disparities (**Figure 3**), as micro-scale studies focus on individual or idealized street canyons, while local scale studies investigate neighborhood areas with realistic urban morphology. Flows in the micro- and local scales are primarily dominated by mesoscale flows[22,23]. Meso-scale (2 km up to 2000 km) flows are regulated by land and sea breeze circulations in coastal areas, thermally induced valley winds, and channeled flow along valleys[24]. At the micro- and local scale, airflow in the street canyon plays a crucial role in facilitating ventilation, heat removal, and pollutant dispersion.

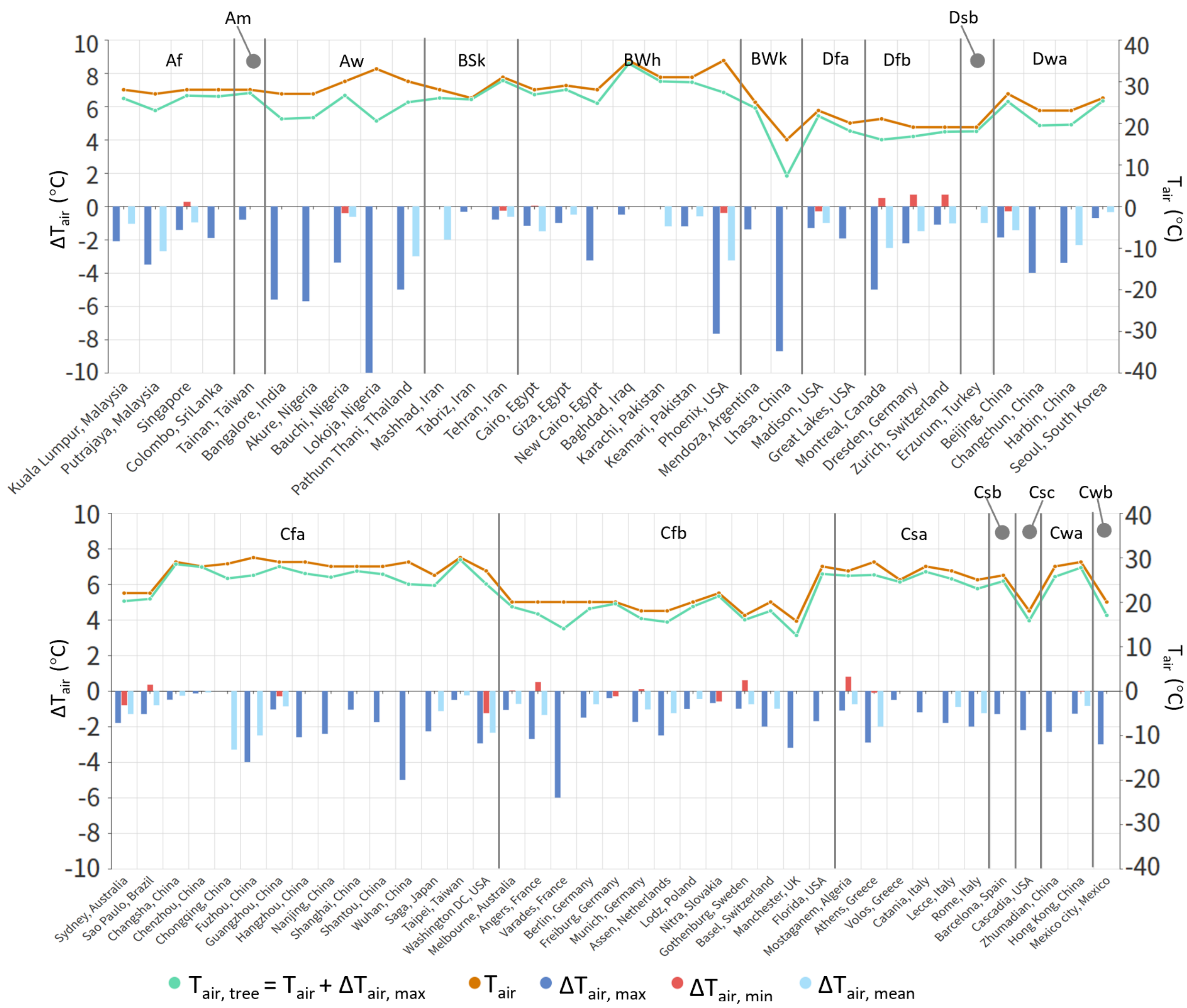

Figure 4. Estimated urban tree cooling potential in 71 major cities or regions. Solid lines compare the achievable air temperature with urban trees ($T_{air,tree}$, green line referring to the right axis) vs. the historically hottest month air temperature observed in the reviewed studies (T_{air}, orange line referring to the right axis). $T_{air,tree}$ represents a lower air temperature cooled by trees, which equals the sum of the historically hottest month air temperature observed (T_{air}) and achievable air temperature reductions ($\Delta T_{air,max}$, blue bar referring to the left axis). Bars in dark blue, red, and light blue represent the reported cooling benefits characterized by $\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively.

Studies on the micro and local scales (up to 2 km) take up more than 80% of the studies, as summarized in **Supplementary C**. **Figure 4** highlights the estimated urban tree cooling potential based on micro and local scale studies. In particular, we report cooling benefits ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) in each city. After the implementation of trees, in 83% of cities, the air temperature of the hottest month was reduced to below 26 °C, meeting the thermal comfort threshold[25].

When comparing absolute temperature reduction (ΔT_{air}) and relative temperature reduction ($\Delta T_{air}/T_{air}$), trees in tropical and arid climates demonstrate more significant cooling effects in absolute terms, while trees in continental and temperate climates offer a higher relative air temperature reduction. In other words, the proportional reduction of air temperature by trees in continental and temperate climates is more pronounced. Therefore, future urban planning initiatives should consider both the relative and absolute impacts of trees' cooling potential concerning local background climates. This approach will enable the implementation of targeted strategies that maximize the cooling potential of trees in respective climates.

Quantification of tree cooling effects influenced by interconnected factors

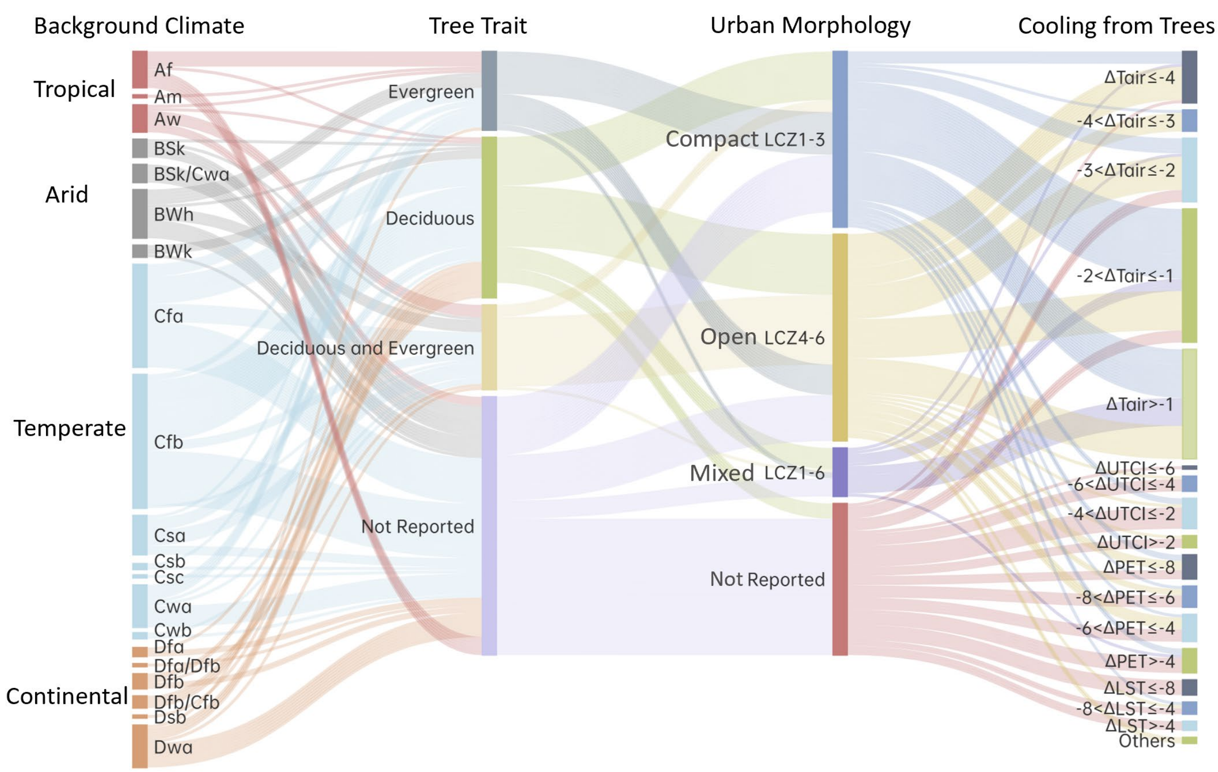

Figure 5. The hidden interconnections of background climate, tree traits, urban morphology characteristics, and the corresponding cooling potentials. The tree traits are characterized by leaf retention types and the urban morphology characteristics are characterized by local climate zone (LCZ). The cooling potential is evaluated using indicators including ΔT_{air}, ΔUTCI, ΔPET, and ΔLST.

Background climate, urban morphology, and tree traits are highly interconnected and can collectively determine urban tree cooling potentials (**Figure 5**). Among the reviewed studies, urban trees in tropical climates are predominantly evergreen. In compact urban forms (LCZ1-3), all studies involve evergreen trees, while in open urban forms (LCZ4-6), 27% of studies involve evergreen trees, 57% involve deciduous trees, and 16% involve mixed species (**Figure 6**). Deciduous trees in tropical and arid climates shed their leaves typically in response to dry seasons rather than cold temperatures[26]. In arid climates, evergreen trees are dominant; around 80% of studies involve evergreen trees, and 20% involve deciduous trees. In temperate and continental climates, there is a mixed use of deciduous and evergreen trees. Tree traits, whether evergreen, deciduous, or a mix of both, are linked to various types of urban morphology, showing a broad distribution across compact, open, and mixed urban forms (**Figure 5**). About 25% of the reviewed articles neither report urban morphology information nor specify tree types.

The cooling effects from trees are quantified in complex dimensions. These results indicate significant variations in tree effects across different climates in terms of cooling efficacy (**Figure 6**). According to the 75th and 25th percentiles of the boxplot, trees exhibit distinct ranges of cooling efficacy ($\Delta T_{air,max}$ and $\Delta T_{air,mean}$) across different climates, which are affected by local weather patterns. In arid climates, the cooling efficacy has an extensive range. The high cooling efficacy is due to high shading potential with low latitudes and high transpirational potential with a high vapor pressure deficit[21], while low cooling efficacy is due to various environmental stressors such as extreme temperatures, dry air and soil, and low tree survival rates [27].

From **Figure 5**, urban tree cooling is primarily quantified by air temperature reduction (ΔT_{air}, 126 case studies). In addition, 30% of studies mainly focused on thermal comfort or thermo-physiological comfort analysis, often using indicators such as UTCI (25 studies) and PET (48 studies). As an example, UTCI calculation (Eq.2) incorporates air temperature (T_{air}), and additional meteorological variables such as relative humidity (RH), wind speed (V_{air}), and mean radiant temperature (T_{mrt}) [10]. Moreover, a few meso-scale remote sensing studies quantified cooling from trees solely based on land surface temperature (LST). The UTCI changes can reach up to -6°C, with most changes ranging from -4°C to -2°C. Similarly, the PET changes can reach up to -8°C, typically ranging from -8°C to -4°C.

$$UTCI = T_{air} + f(T_{air}, T_{mrt}, V_{air}, RH) \quad (2)$$

Studies, in general, show stronger urban tree cooling in open and low-rise areas in dry climates (**Figure 6**). With open urban form LCZ 4-6, the cooling can be improved by about 0.4 °C (**Table 1**). This is mainly due to the availability of larger spaces that allow for greater canopies, higher biodiversity, and more extensive green coverage. On average (as seen in **Table 1**), the temporal mean air temperature, $T_{air,mean}$, shows a higher reduction (-2.14 °C) in arid climates with LC Z4-6, while it is at its lowest (-1.03 °C) in temperate climates with LCZ 1-3. Case studies with mixed-use trees in open urban morphology zones (LCZ4-6) yield more significant cooling effects than those in compact urban morphology zones (LCZ1-3), especially in hot and warm dry climates. These results emphasize the importance of strategic urban planning that incorporates diverse tree types and extensive green spaces to maximize cooling benefits, especially in arid and high-temperature regions.

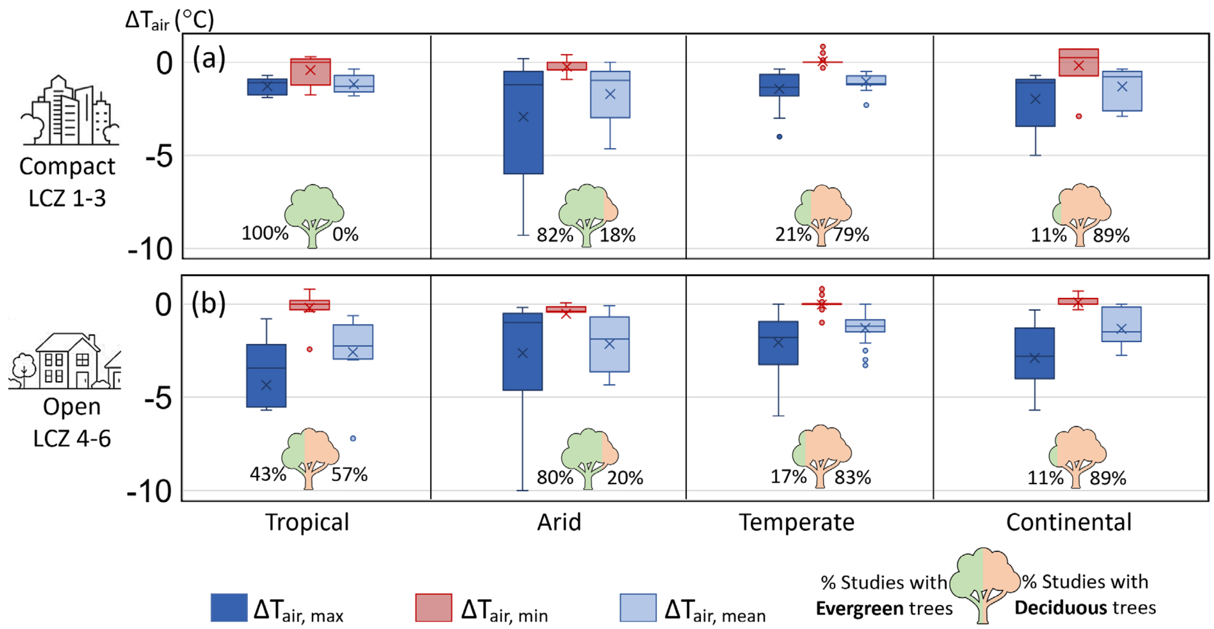

Figure 6. The cooling potential of urban trees evaluated across complex dimensions. The box plots display maximum ($\Delta T_{air,max}$, dark blue), minimum ($\Delta T_{air,min}$, red), and mean ($\Delta T_{air,mean}$, light blue) air temperature reductions and the use of evergreen and deciduous trees, for compact and open urban morphology as well as in tropical, arid, temperate, and continental climates. The box plot's rectangle covers the interquartile range (25th to 75th percentiles). Inside, lines mark the median, and a cross marks the mean. Whiskers extend to the data's minimum and maximum within 1.5 times the interquartile range.

Table 1. Summary of reported cooling efficacy ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) of studies averaged for compact (LCZ 1-3) and open (LCZ 4-6) urban forms, and in tropical, arid, temperate and continental climate groups.

Tropical		**$\Delta T_{air,\ max}$ (°C)**	**$\Delta T_{air,\ min}$ (°C)**	**$\Delta T_{air,\ mean}$ (°C)**
LCZ 1-3	Compact	-1.28	-0.42	-1.18
LCZ 4-6	Open	-4.36	-0.21	-2.57
Arid		**$\Delta T_{air,\ max}$ (°C)**	**$\Delta T_{air,\ min}$ (°C)**	**$\Delta T_{air,\ mean}$ (°C)**
LCZ 1-3	Compact	-2.92	-0.25	-1.72

LCZ 4-6	Open	-2.83	-0.52	-2.14
Temperate		**$\Delta T_{air,\ max}$ (°C)**	**$\Delta T_{air,\ min}$ (°C)**	**$\Delta T_{air,\ mean}$ (°C)**
LCZ 1-3	Compact	-1.42	0.05	-1.03
LCZ 4-6	Open	-2.07	-0.04	-1.33
Continental		**$\Delta T_{air,\ max}$ (°C)**	**$\Delta T_{air,\ min}$ (°C)**	**$\Delta T_{air,\ mean}$ (°C)**
LCZ 1-3	Compact	-1.97	-0.20	-1.31
LCZ 4-6	Open	-2.91	0.14	-1.55

Minor:

1) key points: the four key points, is it the result of one sample study or the reviewing results? If it is the former, I don't think it is appropriate to list it.

Response: We have removed the key point section, as is not required by the journal.

2) The author's objectives seem overly ambitious to me. I find it challenging to draw conclusions to respond to the research question. Where is the trade-off analysis?

Response: Balancing the interconnected factors that influence tree cooling effects involves several key trade-offs: Trees with high transpiration rates offer better cooling but may not be sustainable in water-scarce areas, necessitating a balance between water use and cooling efficiency. Large canopies provide extensive shading but might compete with urban infrastructure and space for pedestrians and buildings, presenting a trade-off between canopy coverage and urban space. Fast-growing species provide quick benefits but might not last as long or could require more frequent replacement and maintenance, highlighting the growth rate versus longevity dilemma. Additionally, while diverse species can create a resilient urban forest, uniformity simplifies maintenance and management, posing a trade-off between species diversity and uniformity.

Although these trade-offs are important to understand, these findings can not be directly concluded from our meta-analysis. Therefore, we have restructured our objectives to be more focused on providing guiding principles with integrated approaches that facilitate tree species selection and tree placement. These planning practices require an understanding of interconnected climate, urban morphology, and tree trait factors, as well as how they influence tree cooling effects.

Revision: Line 397-496

Guiding principles for harnessing cooling effects of urban trees

Findings from our systematic review meta-analysis have important implications for urban heat mitigation practices. We proposed an integrated approach to align key practices, such as tree selection and tree placement, with urban morphology and background climate. We further elaborate on tree-planning strategies for a warming future climate and discuss recent international and national tree-planning initiatives.

An integrated approach: aligning tree selection and placement with urban morphology and climate

"Right tree, right place." The selection of appropriate tree species and their placement in appropriate locations should be based on the available space, growth requirements, and suitable climate conditions to maximize the cooling impact.

This approach ensures that local species can thrive and provide maximum cooling benefits. In general, tree species and the age of the tree determine leaf retention, LAI, LAD, and tree crown morphology, which collectively influence the cooling efficacy of a single tree. In tropical, temperate, and continental climates, reviewed studies show higher biodiversity with various heights of deciduous and evergreen trees. The mixed-use of various species can balance seasonal shading and sunlight, providing three-dimensional cooling at various heights[5,28]. From the reviewed studies, low stomatal resistance species such as *Ulmus americana* can maximize transpiration, though these species are less common in arid climate zones[29]. In high-temperature climates, small-leaved, heat-resistant species such as *Gleditsia triacanthos* L. and *Metasequoia glyptostroboides* are recommended[30]. In dry climates, prioritizing drought-resistant evergreens that maximize shading and tree-trait-driven cooling is crucial[19]. Higher LAI and LAD values of trees correlate with higher cooling potential during the daytime, as the radiation blockage effects of trees are enhanced [31,32]. Variations in air temperature and sensible heat flux, along with the enhancements in latent heat flux, exhibit a non-linear dependency on LAI[33]. The cooling effects also increase nonlinearly with tree height in symmetrical street canyons [34].

Furthermore, the selection of species and tree placement needs to comply with the urban forms. Trees are expected to provide effective cooling at hot spots in cities; therefore, it is suggested that high leaf-density species be planted densely to offer more coverage at hot spot locations, considering the street orientation, airflow patterns, etc. The orientation of the street canyon, LCZ, aspect ratio, SVF, and other urban morphology features that significantly influence the effects of trees should be carefully considered[35–37]. In compact urban forms with relatively low greenery fraction, especially in LCZ 1, trees usually exhibit high vertical growth and narrow crowns; in comparison, in open canopies LCZ 4-6, trees are often planted densely with spreading crowns [30,38], which are more suitable for deciduous trees. The cooling effects of trees increase with tree canopy coverage, which in turn influences SVF beneath trees[33]. Nevertheless, a denser tree arrangement can lead to improved cooling benefits[39]. For example, in Saga, Japan, a 20% increase in the density of trees resulted in a -2.27 °C reduction in air temperature at the peak temperature on a university campus[40].

Although a higher degree of tree canopy cover in street canyons generally results in more significant cooling effects, excessively high tree canopy cover may trap heat at the pedestrian level, especially in LCZ 1-3 compact zones with high background temperature climates [2]. Due to stomatal closure and the absence of solar radiation, transpirational cooling and shading are minimal at nighttime. Improper extensive planting of trees can result in low SVF and weakened micro-scale air ventilation, which causes the trapping of longwave radiation beneath the tree foliage[3–5]. Therefore, in compact urban zones, narrow species and sparse planting strategies are recommended. Additionally, tree species with smaller root systems that fit into limited spaces without causing structural damage to buildings are ideal for roof or terrace gardens. Recent research has demonstrated that integrated greenery provides effective cooling effects and is of vital importance, especially in densely built urban areas (LCZ 1-3) where open ground space is often scarce[6–9]. Trees on building roofs or terraces can effectively block radiation to building surfaces, add aerodynamic resistance, and cool surfaces through shading and evapotranspiration, providing a 1.8–4°C cooling effect at roofs and up to 15°C for indoor temperature reduction[6,7].

Urban trees for heat mitigation in a warming climate

As one of the key factors in the integrated approach, background climates are essential to the cooling effects of urban trees [41,42], which regulate the cooling efficacy and influence the selection of appropriate species. Embedding climatic factors in urban planning and tailoring tree-planting strategies is crucial, especially in the face of global warming.

Our meta-analysis illustrates the significance of background temperature and precipitation on the cooling effects of trees in tropical climates [43]. Cities in arid and tropical climates, generally located at lower latitudes, are subject to intense solar irradiance and high background air temperatures[21,44]. Our findings align with those of Yang et al.[45] and Su et al.[46], demonstrating that the cooling efficacy of trees varies markedly among cities, with higher values attained in hot and dry cities. Given that the vapor pressure within the stomata is near the saturation vapor pressure at the leaf temperature, the potential for transpirational cooling in hot climates is significant and, meanwhile, highly sensitive to environmental humidity levels. Wang et al.[47] conducted meso-scale numerical simulations and compared the near-surface temperature with/without trees across the contiguous United States. Among the six regions, it was found that regions in temperate oceanic climate have relatively lower cooling potential than other climate types.

Given current global warming and increasing precipitation, it is becoming increasingly imperative to reform urban planning policies to embed climate-specific strategies and adapt to future warming. Urban planners should consider choosing resilient species that can thrive in changing climate conditions. Heatwaves can strain trees by increasing their water demand while simultaneously reducing water availability due to higher evapotranspiration rates. Exceptionally high temperatures and extremely high vapor pressure deficits at the hottest hours can cause stomatal closure, which reduces transpirational cooling [21,48,49], particularly in tropical and arid climates. Studies have quantified that during heatwaves, the cooling benefits of urban trees could decrease by up to 30% due to stress-induced stomatal closure and water scarcity[50,51]. This reduction in transpiration can significantly affect the microclimate benefits provided by urban forests, making cities more vulnerable to heat stress. Additionally, prolonged heat stress can lead to tree mortality, further diminishing urban canopy cover and exacerbating the heat island effect. This phenomenon highly depends on tree species. Urban planners should plan for future warmer climates by choosing resilient species, such as anisohydric species, that can thrive in changing climate conditions[52].

On the other hand, trees may take decades to fully mature and deliver the full magnitude of their expected shading benefits[53,54]. Young trees with smaller crowns and root systems may not provide expected shading and may even struggle to survive during hot summers[55]. Given the urgency of global warming and its consequences, waiting for trees to mature over a long period may not be practical. Therefore, when implementing urban trees, it is critical to enhance cooling effects by optimizing tree traits with the consideration of the growth time required. Other complementary shading and evaporation solutions, such as solar shading and reflective materials, are essential in combating future detrimental urban overheating in the short term.

Several international and national tree-planting initiatives have focused on the strategic selection and placement of trees. Most of the initiatives are designed to enrich biodiversity and climate resilience. In Hong Kong, the government's Plantation Enrichment Programme has been instrumental in introducing both exotic and native tree species to improve ecological health upstream and minimize the tree risks downstream[56,57]. Projects like the European Union's 3 Billion Trees initiative encourage the creation of green corridors and urban forests[58]. These initiatives focus on planting trees in a way that connects different green spaces, enhancing the cooling effect across more expansive urban areas. Cities like Singapore have integrated tree planting into their urban planning policies, emphasizing the creation of green roofs and vertical gardens in addition to traditional tree planting. Some cities focus on planting heat-resilient species.

For example, cities in Australia have promoted local species like the Australian eucalyptus and various native trees, which are known for their ability to withstand high temperatures[59].

Our study serves as a database platform that documents global tree-related urban heat mitigation cases, which can facilitate the identification of native tree species and the evaluation of their cooling performance. Adaptation strategies should focus on nature-based solutions that promote local biodiversity and integration with urban infrastructures. Governments can benefit from our study by implementing policies to encourage the planting of native species that are well-adapted to both current and future climate conditions.

Combined graph

3) Figure 1 is very necessary, but I think it now does not reflect the core purpose of the study. The author may consider combining the following three small figures.

Response: Thank you for the suggestion. We have revised **Figure 1** to reflect the core purpose of the study. We emphasize the interconnection between them, and they collectively determine the cooling effects of urban trees.

Revision: Line 48-56

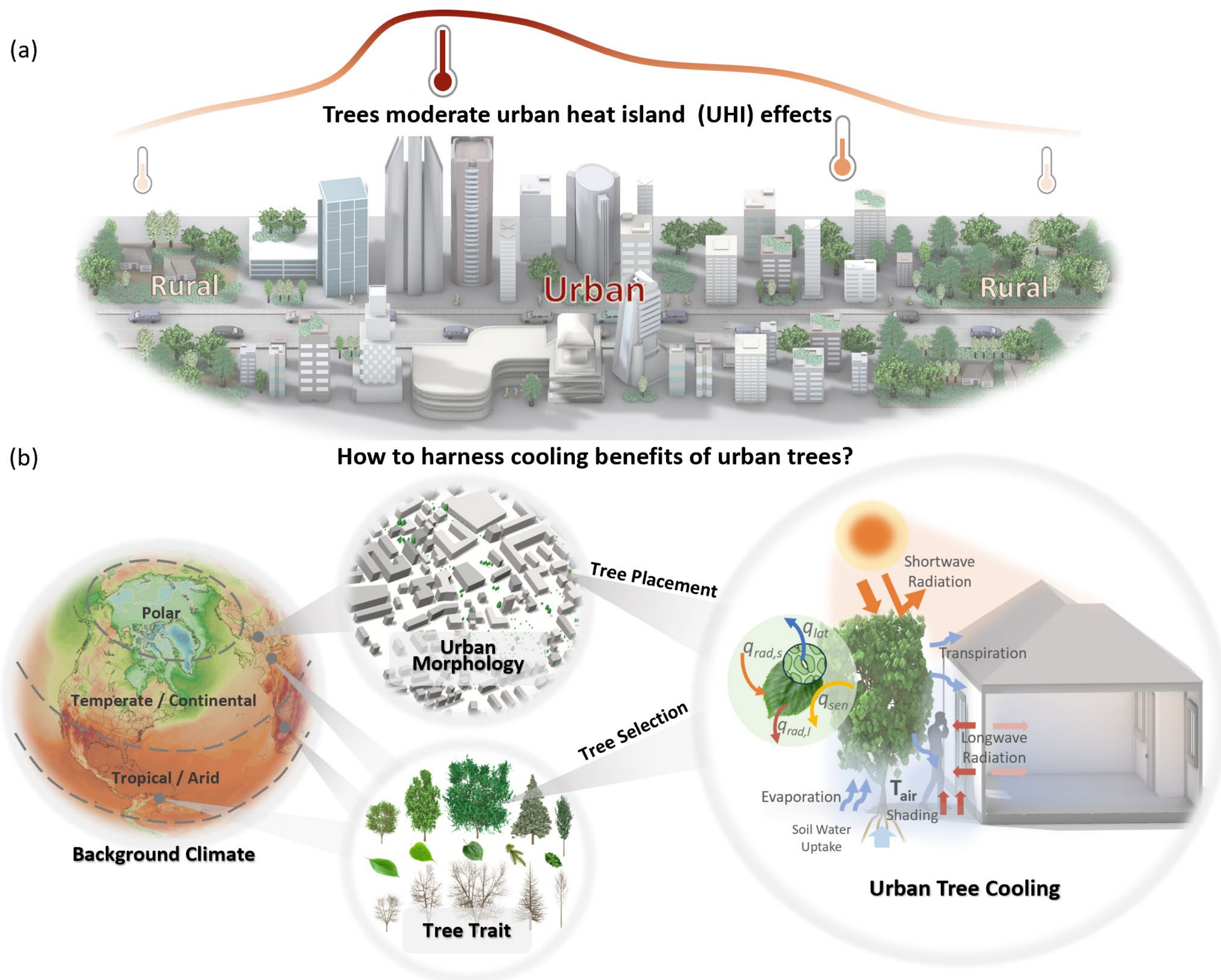

Figure 1. (a) Urban trees moderate urban warming caused by urban heat island (UHI) effects. (b) Interconnecting factors determine the cooling benefits of urban trees. Maximized cooling from urban trees is achieved by selecting the optimal trees and their placement, with an articulated understanding of the interconnecting elements: background climates, tree traits, and urban morphology. The cooling effect of urban trees is determined by a combination of mechanisms, such as shading (shortwave radiation blocking) and transpiration. On the leaf and its stomata scale, the leaf energy balance can be represented by $\boldsymbol{q}_{sen}$(sensible heat flux) + $\boldsymbol{q}_{lat}$(latent heat flux) = $\boldsymbol{q}_{rad,l}$(net longwave radiation) + $\boldsymbol{q}_{rad,s}$(net shortwave radiation).

4) Lines "specifically, in tropical climates, …,at only 0.31°C". It's interesting to do the comparison, but why? What are the theoretical implications of such differences? Or why?

Response: We have reduced and removed content that only focuses on the impacts of background climates and does not necessarily reflect core interconnections. The current quantifications are more focused on quantifying the cooling impacts of trees with interconnected background climate, tree traits, and urban morphological factors.

5) Figures 4 and 5 are redundant because I think the relevant information is already reflected in Figure 6.

Response: Thank you for the suggestion. We combined them, as shown in **Figure 3** in the revised manuscript. We revised this figure and added tree trait and urban morphology information. We still find the figure very useful in terms of showing that the reported cooling magnitudes varied a lot across complex dimensions.

In **Figure 4**, we focus on the impact of trees on major cities. For each city, the cooling effects are estimated from one or more case studies, showing the variations in absolute cooling and relative cooling in different climates. Please find the revisions listed in the section "Interconnections between climate, urban morphology, and tree traits."

Revision: Line 293-299

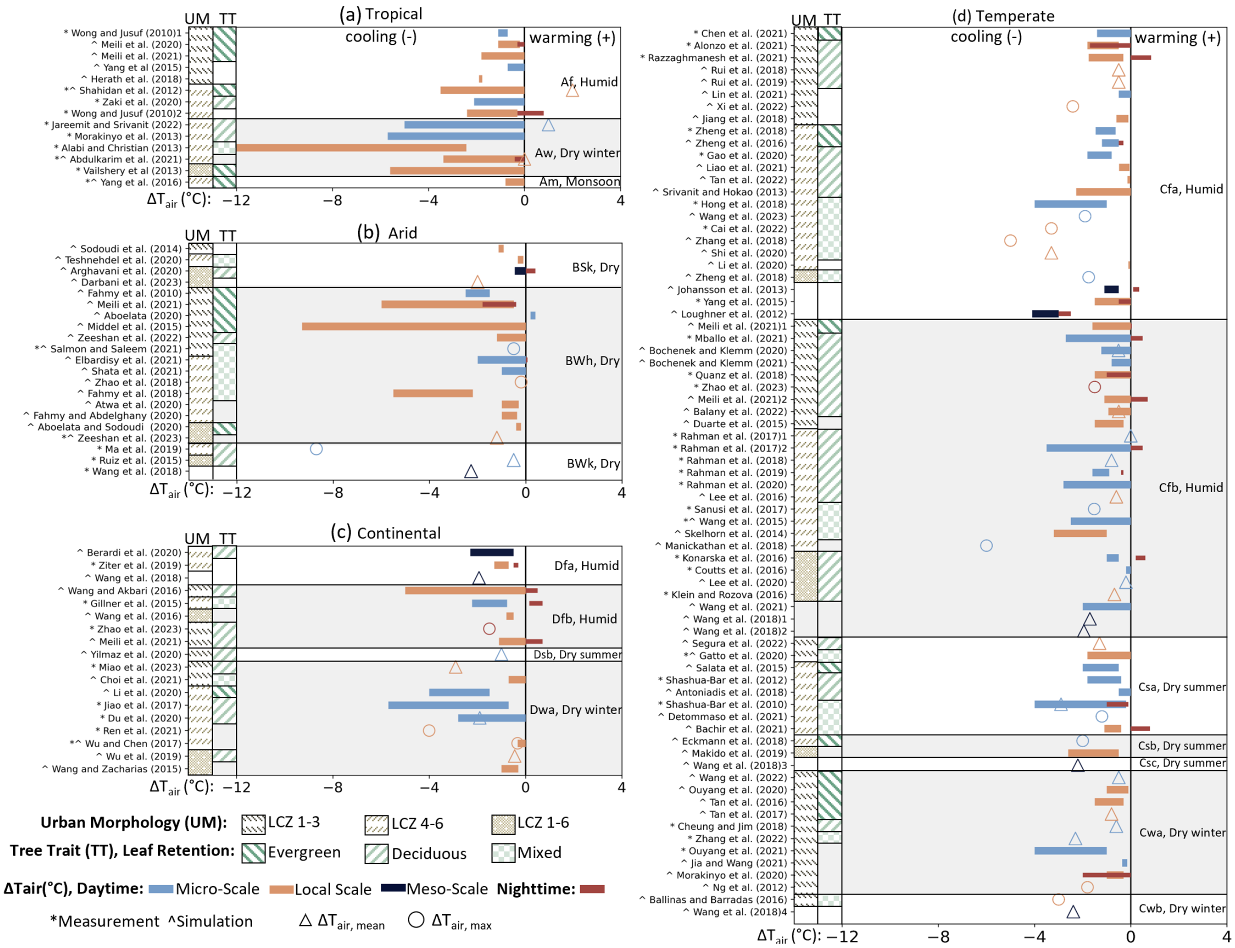

Figure 3. Diurnal variation of ΔT_{air} observed in the (a) tropical, (b) arid, and (c) continental climates. The plotted bars and markers (triangle/circle) represent the cooling or warming efficacy, and the shades in blue, orange and black colors represent the spatial scales on which the cooling or warming was observed. The nighttime effects caused by trees are presented in red. The studies are also classified based on urban morphology (represented by LCZ), tree traits (represented by leaf retention types), and methodologies (measurement or simulation).

Revision: Line 306-310

Studies show that a higher diversity of plant use, particularly the mixed use of various sizes of evergreen and deciduous trees, is linked to open urban forms (LCZ 4-6), often resulting in more significant cooling in tropical, temperate, and continental climates. The combined use of deciduous and evergreen trees generally results in 0.5°C higher cooling compared to studies using only deciduous or evergreen trees in these climates. In arid climates, studies with solely evergreen trees show higher tree cooling potential.

REVISITED 6) Other results are completely unsupported by charts. Some information is expressed in a list of papers. Are there any relevant and clear conclusions that can support the questions you raised earlier?

Response: Although **Figure 3** is presented with a list of key papers, it is crucial as it offers a comprehensive overview of studies related to urban morphology (UM) and tree traits (TT) and their effects on air temperature (ΔT_{air}) across various climates. A synthesized meta-analysis is presented in **Figure 6**, which clearly demonstrates the impact of climate, urban morphology, and tree traits on the cooling potential of urban trees.

Revision: Line 376-392

Studies, in general, show stronger urban tree cooling in open and low-rise areas in dry climates (**Figure 6**). With open urban form LCZ 4-6, the cooling can be improved by about 0.4 °C (**Table 1**). This is mainly due to the availability of larger spaces that allow for greater canopies, higher biodiversity, and more extensive green coverage. On average (as seen in **Table 1**), the temporal mean air temperature, $T_{air,mean}$, shows a higher reduction (-2.14 °C) in arid climates with LC Z4-6, while it is at its lowest (-1.03 °C) in temperate climates with LCZ 1-3. Case studies with mixed-use trees in open urban morphology zones (LCZ4-6) yield more significant cooling effects than those in compact urban morphology zones (LCZ1-3), especially in hot and warm dry climates. These results emphasize the importance of strategic urban planning that incorporates diverse tree types and extensive green spaces to maximize cooling benefits, especially in arid and high-temperature regions.

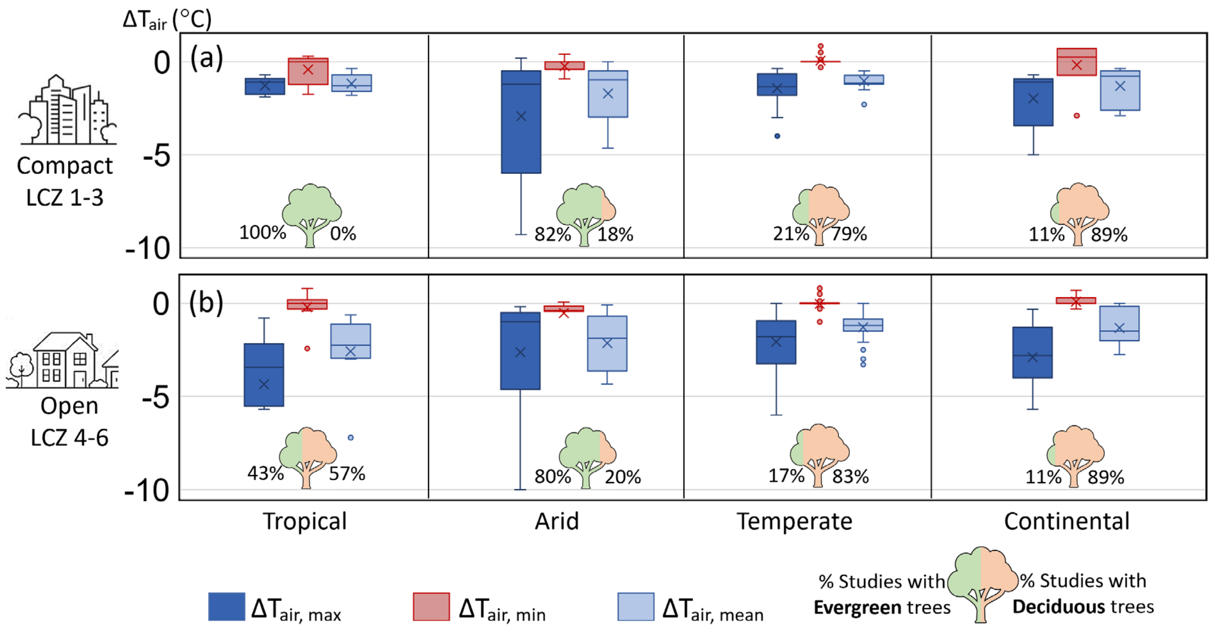

Figure 6. The cooling potential of urban trees evaluated across complex dimensions. The box plots display maximum ($\Delta T_{air,max}$, dark blue), minimum ($\Delta T_{air,min}$, red), and mean ($\Delta T_{air,mean}$, light blue) air temperature reductions and the use of evergreen and deciduous trees, for compact and open urban morphology as well as in tropical, arid, temperate, and continental climates. The box plot's rectangle covers the interquartile range (25th to 75th percentiles). Inside, lines mark the median, and a cross marks the mean. Whiskers extend to the data's minimum and maximum within 1.5 times the interquartile range.

References

1. Bowler, D. E., Buyung-Ali, L., Knight, T. M. & Pullin, A. S. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc Urban Plan* **97**, 147–155 (2010).
2. Huang, X., Song, J., Wang, C., Chui, T. F. M. & Chan, P. W. The synergistic effect of urban heat and moisture islands in a compact high-rise city. *Build Environ* **205**, 108274 (2021).
3. Li, X. & Ratti, C. Mapping the spatial distribution of shade provision of street trees in Boston using Google Street View panoramas. *Urban For Urban Green* **31**, 109–119 (2018).
4. Song, J. & Wang, Z. H. Interfacing the Urban Land–Atmosphere System Through Coupled Urban Canopy and Atmospheric Models. *Boundary Layer Meteorol* **154**, 427–448 (2015).

5. Mehrotra, S., Bardhan, R. & Ramamritham, K. Diurnal thermal diversity in heterogeneous built area: Mumbai, India. *Urban Clim* **32**, 100627 (2020).

6. Hong, T., Wu, X., Chen, Y. & Lin, X. Impact of Roof Greening on the Ecological Environment of the Green Building, Exemplified by the Roof Garden of the Mingde Building in Fujian Agricultural and Forestry University. in *Green City Planning and Practices in Asian Cities: Sustainable Development and Smart Growth in Urban Environments* (eds. Shen, Z., Huang, L., Peng, K. & Pai, J.) 193–209 (Springer International Publishing, Cham, 2018).

7. Tien, P. W., Mohammadi, M. & Calautit, J. K. Providing Comfortable Environment in Skygardens Within High-Rise Buildings: Analysis of the Impact of Vegetation on Wind and Thermal Comfort. *Journal of Sustainable Development of Energy Water and Environment Systems-Jsdewes* **9**, 1–28 (2021).

8. Abass, F., Ismail, L. H., Wahab, I. A. & Elgadi, A. A. A Review of Green Roof: Definition, History, Evolution and Functions. in *IOP Conference Series: Materials Science and Engineering* 012048 (2020).

9. Costanzo, V., Evola, G. & Marletta, L. Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. *Energy Build* **114**, 247–255 (2016).

10. Cheung, P. K. & Jim, C. Y. Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI. *Build Environ* **130**, 49–61 (2018).

11. Oke, T. R., Mills, G., Christen, A. & Voogt, J. A. *Urban Climates*. (Cambridge University Press, Cambridge, 2017).

12. de Quadros, B. M. & Mizgier, M. G. O. Urban green infrastructures to improve pedestrian thermal comfort: A systematic review. *Urban For Urban Green* **88**, 128091 (2023).

13. Jendritzky, G., de Dear, R. & Havenith, G. UTCI-Why another thermal index? *Int J Biometeorol* **56**, 421–428 (2012).

14. Ren, Z., Zhao, H., Fu, Y., Xiao, L. & Dong, Y. Effects of urban street trees on human thermal comfort and physiological indices: a case study in Changchun city, China. *J For Res (Harbin)* **33**, 911–922 (2022).

15. Jareemit, D. & Srivanit, M. A Comparative Study of Cooling Performance and Thermal Comfort under Street Market Shades and Tree Canopies in Tropical Savanna Climate. *Sustainability* **14**, 4653 (2022).

16. Vailshery, L. S., Jaganmohan, M. & Nagendra, H. Effect of street trees on microclimate and air pollution in a tropical city. *Urban For Urban Green* **12**, 408–415 (2013).

17. Alabi, M. O. & Christian, E. I. Street Tree Canopy Cover Variation Effects on Temperature in Lokoja, Nigeria. *Journal of Agriculture and Environmental Science* **2**, 25–31 (2013).

18. Wang, Y. P. & Akbari, H. The effects of street tree planting on Urban Heat Island mitigation in Montreal. *Sustain Cities Soc* **27**, 122–128 (2016).

19. Gillner, S., Vogt, J., Tharang, A., Dettmann, S. & Roloff, A. Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landsc Urban Plan* **143**, 33–42 (2015).

20. Zhao, Y. *et al.* The time-evolving impact of tree size on nighttime street canyon microclimate: Wind tunnel modeling of aerodynamic effects and heat removal. *Urban Clim* **49**, 101528 (2023).

21. Meili, N. *et al.* Tree effects on urban microclimate: Diurnal, seasonal, and climatic temperature differences explained by separating radiation, evapotranspiration, and roughness effects. *Urban For Urban Green* **58**, 126970 (2021).

22. Kong, J., Zhao, Y., Carmeliet, J. & Lei, C. Urban Heat Island and Its Interaction with Heatwaves: A Review of Studies on Mesoscale. *Sustainability* **13**, 10923 (2021).

23. Krayenhoff, E. S. *et al.* Cooling hot cities: a systematic and critical review of the numerical modelling literature. *Environmental Research Letters* vol. 16 053007 Preprint at https://doi.org/10.1088/1748-9326/abdcf1 (2021).

24. Berardi, U., Jandaghian, Z. & Graham, J. Effects of greenery enhancements for the resilience to heat waves: A comparison of analysis performed through mesoscale (WRF) and microscale (Envi-met) modeling. *Science of The Total Environment* **747**, 141300 (2020).

25. ASHRAE. *ASHRAE Handbook Fundamentals 2005*. *Book* (2005).

26. Zeeshan, M., Ali, Z., Sajid, M., Ali, M. & Usman, M. Modelling the cooling effectiveness of street trees with actual canopy drag and real transpiration rate under representative climatic conditions. *J Build Perform Simul* **1**, 1–14 (2022).

27. Medina, S. *et al.* The plant-transpiration response to vapor pressure deficit (VPD) in durum wheat is associated with differential yield performance and specific expression of genes involved in primary metabolism and water transport. *Front Plant Sci* **9**, 1994 (2019).

28. Alvey, A. A. Promoting and preserving biodiversity in the urban forest. *Urban For Urban Green* **5**, 195–201 (2006).

29. Cheung, P. K., Livesley, S. J. & Nice, K. A. Estimating the cooling potential of irrigating green spaces in 100 global cities with arid, temperate or continental climates. *Sustain Cities Soc* **71**, 102974 (2021).

30. Rahman, M. A. *et al.* Traits of trees for cooling urban heat islands: A meta-analysis. *Build Environ* **170**, 106606 (2020).

31. Feng, L., Yang, S., Zhou, Y. & Shuai, L. Exploring the effects of the spatial arrangement and leaf area density of trees on building wall temperature. *Build Environ* **205**, 108295 (2021).

32. Cai, Y. *et al.* Effect of the roadside tree canopy structure and the surrounding on the daytime urban air temperature in summer. *Agric For Meteorol* **316**, 108850 (2022).

33. Wang, C., Wang, Z. H. & Ryu, Y. H. A single-layer urban canopy model with transmissive radiation exchange between trees and street canyons. *Build Environ* **191**, 107593 (2021).

34. Yang, Y. J. *et al.* Simulation on the impacts of the street tree pattern on built summer thermal comfort in cold region of China. *Sustain Cities Soc* **37**, 563–580 (2018).

35. Rahman, M. A. *et al.* Tree cooling effects and human thermal comfort under contrasting species and sites. *Agric For Meteorol* **287**, 107947 (2020).

36. Srivanit, M. & Jareemit, D. Modeling the influences of layouts of residential townhouses and tree-planting patterns on outdoor thermal comfort in Bangkok suburb. *Journal of Building Engineering* **30**, 101262 (2020).

37. Zaki, S. A. *et al.* Effects of Roadside Trees and Road Orientation on Thermal Environment in a Tropical City. *Sustainability* **12**, 1053 (2020).

38. Liu, Z. *et al.* Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Build Environ* **200**, 107939 (2021).

39. Coutts, A. M., White, E. C., Tapper, N. J., Beringer, J. & Livesley, S. J. Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. *Theor Appl Climatol* **124**, 55–68 (2016).

40. Srivanit, M. & Hokao, K. Evaluating the cooling effects of greening for improving the outdoor thermal environment at an institutional campus in the summer. *Build Environ* **66**, 158–172 (2013).

41. Potchter, O. & Shashua-Bar, L. Urban greenery as a tool for city cooling: The Israeli experience in a variety of climatic zones. in *Proceedings of 33rd PLEA International Conference: Design to Thrive, PLEA 2017* vol. 2 (2017).

42. Yu, Z., Xu, S., Zhang, Y., Jørgensen, G. & Vejre, H. Strong contributions of local background climate to the cooling effect of urban green vegetation. *Sci Rep* **8**, 6798 (2018).

43. Wang, C. *et al.* Efficient cooling of cities at global scale using urban green space to mitigate urban heat island effects in different climatic regions. *Urban For Urban Green* **74**, 127635 (2022).

44. Cheng, X., Peng, J., Dong, J., Liu, Y. & Wang, Y. Non-linear effects of meteorological variables on cooling efficiency of African urban trees. *Environ Int* **169**, 107489 (2022).

45. Yang, Q. *et al.* Global assessment of urban trees' cooling efficiency based on satellite observations. *Environmental Research Letters* **17**, 034029 (2022).

46. Su, Y. *et al.* Estimating the cooling effect magnitude of urban vegetation in different climate zones using multi-source remote sensing. *Urban Clim* **43**, 101155 (2022).

47. Wang, C., Wang, Z.-H. & Yang, J. Cooling Effect of Urban Trees on the Built Environment of Contiguous United States. *Earths Future* **6**, 1066–1081 (2018).

48. Chen, L. *et al.* Biophysical control of whole tree transpiration under an urban environment in Northern China. *J Hydrol (Amst)* **402**, 388–400 (2011).

49. Gillner, S., Korn, S., Hofmann, M. & Roloff, A. Contrasting strategies for tree species to cope with heat and dry conditions at urban sites. *Urban Ecosyst* **20**, 853–865 (2017).

50. Ji, L., Shu, C., Gaur, A., Wang, L. & Lacasse, M. A state-of-the-art review of studies on urban green infrastructure for thermal resilient communities. *Build Environ* **257**, 111524 (2024).

51. Klein, T. The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. *Funct Ecol* **28**, 1313–1320 (2014).

52. Garcia-Forner, N. *et al.* Responses of two semiarid conifer tree species to reduced precipitation and warming reveal new perspectives for stomatal regulation. *Plant Cell Environ* **39**, 38–49 (2016).

53. McPherson, E. G. A benefit-cost analysis of ten street tree species in Modesto, California, U.S. *Journal of Arboriculture* **29**, 1–8 (2003).

54. Song, X. P., Tan, P. Y., Edwards, P. & Richards, D. The economic benefits and costs of trees in urban forest stewardship: A systematic review. *Urban For Urban Green* **29**, 162–170 (2018).

55. Li, H. *et al.* Time-evolving Impact of Trees on Street Canyon Microclimate. *J Phys Conf Ser* **2654**, 012145 (2023).

56. Zhang, H. & Jim, C. Y. Species adoption for sustainable forestry in Hong Kong's degraded countryside. *International Journal of Sustainable Development and World Ecology* **20**, 484–503 (2013).

57. Lee, E. W. S., Hau, B. C. H. & Corlett, R. T. Natural regeneration in exotic tree plantations in Hong Kong, China. *For Ecol Manage* **212**, 358–366 (2005).

58. Lee, H. *et al.* Three billion new trees in the EU's biodiversity strategy: low ambition, but better environmental outcomes? *Environmental Research Letters* **18**, 034020 (2023).

59. Merchant, A., Callister, A., Arndt, S., Tausz, M. & Adams, M. Contrasting physiological responses of six Eucalyptus species to water deficit. *Ann Bot* **100**, 1507–1515 (2007).

60. Manickathan, L., Defraeye, T., Allegrini, J., Derome, D. & Carmeliet, J. Parametric study of the influence of environmental factors and tree properties on the transpirative cooling effect of trees. *Agric For Meteorol* **248**, 259–274 (2018).

61. Wang, C., Li, Q. & Wang, Z. H. Quantifying the impact of urban trees on passive pollutant dispersion using a coupled large-eddy simulation–Lagrangian stochastic model. *Build Environ* **145**, 33–49 (2018).

62. Meili, N. *et al.* An urban ecohydrological model to quantify the effect of vegetation on urban climate and hydrology (UT&C v1.0). *Geosci Model Dev* **13**, 335–362 (2020).

63. Krayenhoff, E. S. *et al.* A multi-layer urban canopy meteorological model with trees (BEP-Tree): Street tree impacts on pedestrian-level climate. *Urban Clim* **32**, 100590 (2020).

64. Johansson, E., Spangenberg, J., Gouvea, M. L. & Freitas, E. D. Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of Sao Paulo, Brazil. *Urban Clim* **6**, 24–43 (2013).

65. Morakinyo, T. E., Kong, L., Lau, K. K. L., Yuan, C. & Ng, E. A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. *Build Environ* **115**, 1–17 (2017).

66. Morakinyo, T. E., Ouyang, W. L., Lau, K. K. L., Ren, C. & Ng, E. Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation - development and evaluation. *Science of The Total Environment* **719**, 137461 (2020).

67. Mussetti, G. *et al.* COSMO-BEP-Tree v1.0: a coupled urban climate model with explicit representation of street trees. *Geosci Model Dev* **13**, 1685–1710 (2020).

68. Navalgund, R. R., Jayaraman, V. & Roy, P. S. Remote sensing applications: An overview. *Curr Sci* **93**, 1747–1766 (2007).

69. Zhao, J., Meili, N., Zhao, X. & Fatichi, S. Urban vegetation cooling potential during heatwaves depends on background climate. *Environmental Research Letters* **18**, 014035 (2023).

70. Lindberg, F., Thorsson, S., Rayner, D. & Lau, K. The impact of urban planning strategies on heat stress in a climate-change perspective. *Sustain Cities Soc* **25**, 1–12 (2016).

71. Kent, C. W., Grimmond, S. & Gatey, D. Aerodynamic roughness parameters in cities: Inclusion of vegetation. *Journal of Wind Engineering and Industrial Aerodynamics* **169**, 168–176 (2017).

72. Wu, Z., Dou, P. & Chen, L. Comparative and combinative cooling effects of different spatial arrangements of buildings and trees on microclimate. *Sustain Cities Soc* **51**, 101711 (2019).

73. Speak, A., Montagnani, L., Wellstein, C. & Zerbe, S. The influence of tree traits on urban ground surface shade cooling. *Landsc Urban Plan* **197**, 103748 (2020).

74. Shashua-Bar, L., Pearlmutter, D. & Erell, E. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landsc Urban Plan* **92**, 179–186 (2009).

75. Morakinyo, T. E. & Lam, Y. F. Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. *Build Environ* **103**, 262–275 (2016).

76. Rahman, M. A., Moser, A., Rötzer, T. & Pauleit, S. Comparing the transpirational and shading effects of two contrasting urban tree species. *Urban Ecosyst* **22**, 683–697 (2019).

77. Rahman, M. A., Moser, A., Rötzer, T. & Pauleit, S. Within canopy temperature differences and cooling ability of Tilia cordata trees grown in urban conditions. *Build Environ* **114**, (2017).

78. Lakshmisha, A., Nazar, A. F. & Nagendra, H. Nature based solutions in cities of the global South—The 'where, who and how' of implementation. *Environmental Research: Ecology* **3**, 025005 (2024).

79. Aram, F., Higueras García, E., Solgi, E. & Mansournia, S. Urban green space cooling effect in cities. *Heliyon* **5**, e01339 (2019).

80. Adegun, O. B., Ikudayisi, A. E., Morakinyo, T. E. & Olusoga, O. O. Urban green infrastructure in Nigeria: A review. *Sci Afr* **14**, e01044 (2021).

81. Ramakreshnan, L. & Aghamohammadi, N. The Application of Nature-Based Solutions for Urban Heat Island Mitigation in Asia: Progress, Challenges, and Recommendations. *Curr Environ Health Rep* **11**, 4–17 (2024).

82. Kumar, P. *et al.* Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. *Innovation* **5**, 100588 (2024).

83. Antoszewski, P., Świerk, D. & Krzyżaniak, M. Statistical review of quality parameters of blue-green infrastructure elements important in mitigating the effect of the urban heat island in the temperate climate (C) zone. *Int J Environ Res Public Health* **17**, 7093 (2020).

84. Priya, U. K. & Senthil, R. A review of the impact of the green landscape interventions on the urban microclimate of tropical areas. *Build Environ* **205**, 108190 (2021).

85. Wong, N. H., Tan, C. L., Kolokotsa, D. D. & Takebayashi, H. Greenery as a mitigation and adaptation strategy to urban heat. *Nat Rev Earth Environ* **2**, 166–171 (2021).

86. Galalizadeh, S., Morrison-Saunders, A., Horwitz, P., Silberstein, R. & Blake, D. The cooling impact of urban greening: A systematic review of methodologies and data sources. *Urban For Urban Green* **95**, 128157 (2024).

87. National Aeronautics and Space Administration. NASA Clocks July 2023 as Hottest Month on Record Ever Since 1880. *https://www.nasa.gov/news-release/nasa-clocks-july-2023-as-hottest-month-on-record-ever-since-1880.* (2023).

88. Stewart, I. D. & Oke, T. R. Local climate zones for urban temperature studies. *Bull Am Meteorol Soc* **93**, 1879–1900 (2012).

89. Morakinyo, T. E., Dahanayake, K. W. D. K. C., Adegun, O. B. & Balogun, A. A. Modelling the effect of tree-shading on summer indoor and outdoor thermal condition of two similar buildings in a Nigerian university. *Energy Build* **130**, 720–732 (2016).

90. Aboelata, A. & Sodoudi, S. Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. *Build Environ* **168**, 106490 (2020).

91. Enete, I., Ogbonna, C. & Officha, M. Using trees as urban heat island reduction tool in Enugu city Nigeria based on their air pollution tolerance index. *Ethiopian Journal of Environmental Studies and Management* **5**, 482–486 (2012).

92. Bherwani, H., Singh, A. & Kumar, R. Assessment methods of urban microclimate and its parameters: A critical review to take the research from lab to land. *Urban Clim* **34**, 100690 (2020).

93. Salata, F., Golasi, I., Vollaro, A. D. & Vollaro, R. D. How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. *Energy Build* **99**, 32–49 (2015).

94. Li, G. G., Ren, Z. H. & Zhan, C. H. Sky View Factor-based correlation of landscape morphology and the thermal environment of street canyons: A case study of Harbin, China. *Build Environ* **169**, 106587 (2020).

95. De Luca, F. Outdoor Comfort Analysis in a University Campus During the Warm Season and Parametric Design of Mitigation Strategies for Resilient Urban Environments. *Computer-Aided Architectural Design: Design Imperatives: The Future Is Now* **1465**, 473–493 (2022).

96. Xi, C., Ding, J. W., Wang, J. Q., Feng, Z. B. & Cao, S. J. Nature-based solution of greenery configuration design by comprehensive benefit evaluation of microclimate environment and carbon sequestration. *Energy Build* **270**, 112264 (2022).

97. Shata, R. O., Mahmoud, A. H. & Fahmy, M. Correlating the Sky View Factor with the Pedestrian Thermal Environment in a Hot Arid University Campus Plaza. *Sustainability* **13**, 468 (2021).

98. Aminipouri, M. *et al.* Urban tree planting to maintain outdoor thermal comfort under climate change: The case of Vancouver's local climate zones. *Build Environ* **158**, 226–236 (2019).

99. Azcarate, I., Acero, J. A., Garmendia, L. & Roji, E. Tree layout methodology for shading pedestrian zones: Thermal comfort study in Bilbao (Northern Iberian Peninsula). *Sustain Cities Soc* **72**, 102996 (2021).

100. Zhao, Q. S., Yang, J. C., Wang, Z. H. & Wentz, E. A. Assessing the Cooling Benefits of Tree Shade by an Outdoor Urban Physical Scale Model at Tempe, AZ. *Urban Science* **2**, 4 (2018).

101. Ryu, Y. H., Bou-Zeid, E., Wang, Z. H. & Smith, J. A. Realistic Representation of Trees in an Urban Canopy Model. *Boundary Layer Meteorol* **159**, 193–220 (2016).

102. Upreti, R., Wang, Z. H. & Yang, J. Radiative shading effect of urban trees on cooling the regional built environment. *Urban For Urban Green* **26**, 18–24 (2017).

103. Krayenhoff, E. S., Christen, A., Martilli, A. & Oke, T. R. A Multi-layer Radiation Model for Urban Neighbourhoods with Trees. *Boundary Layer Meteorol* **151**, 139–178 (2014).

104. Wang, Z. H. Monte Carlo simulations of radiative heat exchange in a street canyon with trees. *Solar Energy* **110**, 704–713 (2014).

105. Arghavani, S., Malakooti, H. & Bidokhti, A. A. A. A. Numerical assessment of the urban green space scenarios on urban heat island and thermal comfort level in Tehran Metropolis. *J Clean Prod* **261**, 121183 (2020).

106. Loughner, C. P. *et al.* Roles of Urban Tree Canopy and Buildings in Urban Heat Island Effects: Parameterization and Preliminary Results. *J Appl Meteorol Climatol* **51**, 1775–1793 (2012).

107. Morabito, M. *et al.* Surface urban heat islands in Italian metropolitan cities: Tree cover and impervious surface influences. *Science of The Total Environment* **751**, 142334 (2021).

108. He, C., Zhou, L., Yao, Y., Ma, W. & Kinney, P. L. Cooling effect of urban trees and its spatiotemporal characteristics: A comparative study. *Build Environ* **204**, 108103 (2021).

109. Li, Y. *et al.* Quantifying tree canopy coverage threshold of typical residential quarters considering human thermal comfort and heat dynamics under extreme heat. *Build Environ* **233**, 110100 (2023).

110. Tan, Z., Lau, K. K. L. & Ng, E. Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. *Energy Build* **114**, 265–274 (2016).

111. Lau, K. K. L., Chung, S. C. & Ren, C. Outdoor thermal comfort in different urban settings of sub-tropical high-density cities: An approach of adopting local climate zone (LCZ) classification. *Build Environ* **154**, 227–238 (2019).

112. Moher, D., Liberati, A., Tetzlaff, J. & Altman, D. G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Ann Intern Med* **151**, 264–269 (2009).

Response to Referees

Reviewer #1 (Remarks to the Author):

Congrats to the authors that this revised manuscript is more comprehensive and provided new perspectives from a more "organic' review.

Response to Reviewer #1: We appreciate the valuable comments from Reviewer #1. In this response, we highlighted the importance of our findings, the key beneficiaries, and the novelty of our research questions. Meanwhile, we have improved the manuscript to emphasize these points further. The comments are marked in **bold font**. The revisions are highlighted in blue.

1. However, it is not very clear why do we need to know these findings? Who will benefit from them?

Response: Urban planners and stakeholders often consider trees as the ultimate panacea for mitigating heat stress, implying consistent cooling effects from trees globally, regardless of local climate and urbanization. This study highlights the variability in tree cooling efficacy and emphasizes the need for context-specific cooling strategies, revealing the complex dependence of tree cooling on three primary factors: tree traits, urban morphology, and climate conditions.

This research comprehensively analyzes these various factors, moving beyond generic greening strategies to address city-specific nuances that affect cooling potential. By offering vital insights into the role of urban trees in mitigating the urban heat island (UHI) effect—threatening the well-being of 4.5 billion urban residents—our study underscores the essential role of tree-based cooling in designing livable cities.

Key beneficiaries of this research include academics, urban planners, environmental agencies, and policymakers involved in urban warming mitigation. Our evidence-based guidelines optimize tree-based cooling strategies to maximize effectiveness. Additionally, we developed an interactive database and map documenting hundreds of case studies on tree-based cooling strategies across diverse climates and urban forms. This accessible tool allows users to estimate the potential cooling impact of specific strategies based on comparable urban environments. Moreover, our work supports broader sustainability efforts, aiding local governments and communities in achieving the United Nations Sustainable Development Goals (SDGs), particularly those focused on good health and well-being (SDG 3), sustainable cities (SDG 11), climate action (SDG 13), and life on land (SDG 15).

We have now highlighted the importance and benefits of our findings in a clearer way in the Abstract, Introduction and Conclusion.

Abstract Revision: Line 14-16

Urban planners and other stakeholders often view trees as the ultimate panacea for mitigating urban heat stress; however, their cooling efficacy varies globally and is influenced by three primary factors: tree traits, urban morphology, and climate conditions.

Abstract Revision: Line 22-23

Our study offers context-specific greening guidelines for urban planners to harness tree cooling in the face of global warming.

Introduction Revision: Line 64-71

Although background climate[1–4], urban morphology[4–6], and tree traits[2,3,7,8] are frequently mentioned in numerous case studies, they are often discussed in a fragmented manner without adequate quantification or synthesis related to cooling potential. With the growing body of case studies on the cooling effects of urban trees, our research fills the gap by offering cooling efficacy estimations and guiding principles for urban tree strategies across diverse global contexts. This synthesis of factors represents a comprehensive approach to quantitatively understanding urban tree cooling efficacy, allowing for more generalizable and actionable principles that can be applied across different urban contexts worldwide.

Conclusion Revision: Line 364-376

We provide evidence-based guidelines that account for variations across different climates and various local climate zones (LCZ) to maximize trees' cooling benefits. An integrated approach requires selecting tree species that complement local climate suitability, available ground spaces, and future climate conditions. Balancing the urgency of combating urban overheating with the extended timeline for tree maturity is crucial, as trees require time to reach optimal sizes for adequate cooling. We also developed an interactive database and map, documenting hundreds of case studies worldwide on tree-based urban cooling solutions. Our database enables users to estimate the cooling efficacy of strategies based on data from cities with similar climates and urban structures. In addition, this work supports broader sustainability goals, benefiting local governments and communities committed to achieving SDGs, particularly good health and well-being (SDG 3), sustainable cities (SDG 11), climate action (SDG 13), and life on land (SDG 15).

In summary, our detailed categorization of current research on the cooling effects of urban trees serves as a critical resource for researchers, urban planners, environmental agencies, and policymakers in designing effective strategies for heat mitigation.

3. Are the research questions largely different from previous ones? In this matter, the significance and novelty of the study have not reached the high standards of this journal.

Response: Our research makes a distinct contribution compared to previous studies. While past reviews have largely focused on comparing various urban blue and green strategies, these various strategies involve fundamentally different cooling mechanisms.

In contrast, our study specifically examines urban trees, providing a thorough analysis of their cooling efficacy through critical factors such as tree traits, urban morphology, and climate conditions. Urban trees have unique and powerful cooling mechanisms, primarily through substantial shading and evapotranspiration–that interact with urban environments in ways that enhance cooling. Moreover, our study provides quantifiable metrics of cooling across local climate zones and different tree types–an aspect that previous studies have not addressed in a systematic, comparative manner.

With over a hundred case studies on the cooling effects of urban trees now available, our work fills a critical gap by providing robust cooling efficacy estimations and actionable guiding principles for urban tree strategies across diverse global contexts. As a result, our research is more comprehensive and provides actionable tree-planting guidelines for urban planners and policymakers focused on urban heat mitigation.

Revision: Line 55-71

Past studies have compared various urban green strategies[1,9–13], with the majority comparing various green and blue infrastructures[5,7,8,14]. These greening strategies, however, involve fundamentally different cooling mechanisms, and past reviews have only provided general comparisons. Research has focused on specific climates or regions, such as temperate[8] or tropical climates[15], South Africa[9,12], and Asia[14]. A meta-analysis on tree traits has highlighted that tree canopy density influences cooling benefits, with notable variations based on climate, tree size, ground surface cover, and leaf traits[3]. A recent systematic review has pointed out a lack of quantification regarding the impact of local climate zones and land cover[1].

There remains a notable gap in understanding the cooling potential of urban trees, especially considering their unique cooling mechanisms and interactions with urban features, such as substantial contributions to shading and evapotranspiration. Although background climate[1–4], urban morphology[4–6], and tree traits[2,3,7,8] are frequently mentioned in numerous case studies, they are often discussed in a fragmented manner without adequate quantification or synthesis related to cooling potential. With the growing body of case studies on the cooling effects of urban trees, our research fills the gap by offering cooling efficacy estimations and guiding principles for urban tree strategies across diverse global contexts. This synthesis of factors represents a comprehensive approach to quantitatively understanding urban tree cooling efficacy, allowing for more generalizable and actionable principles that can be applied across different urban contexts worldwide.

Reviewer #3 (Remarks to the Author):

I would like to thanks the Authors for addressing my comments. I consider that the manuscript has improved according to the suggestion and I would like to recommend for its acceptance.

Kind regards

Response to Reviewer #3:

We are pleased that the revisions have met your expectations, and we greatly appreciate your recommendation for acceptance.

Reviewer #4 (Remarks to the Author):

1. I appreciate the author's responses to my concerns regarding a small number of papers in this review. My main worry was that some relevant papers might have been missed, as the first version focused largely on the effects of climate on temperature reduction, while the authors aim to explore the combined effects of climate, urban morphology, and tree traits. Now, thank you for the very clear methods section. I now have a full understanding of the review process, as will the readers. All my concerns have been addressed in this revision.

Response to Reviewer #4:

We sincerely thank the reviewer for their feedback and appreciation of the revised manuscript. We are glad that our revision provided a clearer understanding of our review process and addressed your concerns.

2. I have just one minor suggestion. Since the authors mentioned a review covering articles published before 2010 and have now focused on papers published after 2010, are there any significant differences in findings between these two reviews? If so, I suggest the authors highlight them. If not, no further detail is needed.

Response: Yes, our research offers a distinct contribution. The previous review paper focused broadly on heat mitigation through various greening strategies, but only 11 of the 74 studies specifically addressed urban trees; the rest examined other green infrastructures like green roofs, grass, parks, and forests primarily in urban context[13]. These greening strategies have fundamentally different cooling mechanisms, and previous reviews provided only general comparisons due to the limited number of studies on urban trees.

In contrast, our study focuses specifically on urban trees, analyzing their cooling efficacy in relation to critical factors such as tree traits, urban features, and climate conditions. Urban trees have unique and powerful cooling mechanisms, primarily through substantial shading and evapotranspiration, which interact with urban environments in ways that enhance cooling. The growing body of research on the cooling effects of urban trees now includes over a hundred case studies. With this extensive dataset, we offer guiding principles and cooling efficacy estimations for urban tree strategies across diverse global contexts. As a result, our research is more comprehensive and provides actionable urban greening guidelines, positioning trees as essential tools for heat stress mitigation measures for urban planners, policymakers and other stakeholders.

Revision: Line 55-71

Past studies have compared various urban green strategies[1,9–13], with the majority comparing various green and blue infrastructures[5,7,8,14]. These greening strategies, however, involve fundamentally different cooling mechanisms, and past reviews have only provided general comparisons. Research has focused on specific climates or regions, such as temperate[8] or tropical climates[15], South Africa[9,12], and Asia[14]. A meta-analysis on tree traits has highlighted that tree canopy density influences cooling benefits, with notable variations based on climate, tree size, ground surface cover, and leaf traits[3]. A recent systematic review has pointed out a lack of quantification regarding the impact of local climate zones and land cover[1].

There remains a notable gap in understanding the cooling potential of urban trees, especially considering their unique cooling mechanisms and interactions with urban features, such as substantial contributions to shading and evapotranspiration. Although background climate[1–4], urban morphology[4–6], and tree traits[2,3,7,8] are frequently mentioned in numerous case studies, they are often discussed in a fragmented manner without adequate quantification or synthesis related to cooling potential. With the growing body of case studies on the cooling effects of urban trees, our research fills the gap by offering cooling efficacy estimations and guiding principles for urban tree strategies across diverse global contexts. This synthesis of factors represents a comprehensive approach to quantitatively understanding urban tree cooling efficacy, allowing for more generalizable and actionable principles that can be applied across different urban contexts worldwide.

3. Overall, I recommend publication, as this comprehensive review on temperature reduction, integrating these factors, would provide valuable guidance to urban planners and policymakers.

Response: We are grateful for your recommendation for publication.

References

1. Krayenhoff, E. S. *et al.* Cooling hot cities: a systematic and critical review of the numerical modelling literature. *Environmental Research Letters* **16**, 053007 (2021).

2. de Quadros, B. M. & Mizgier, M. G. O. Urban green infrastructures to improve pedestrian thermal comfort: A systematic review. *Urban For Urban Green* **88**, 128091 (2023).

3. Rahman, M. A. *et al.* Traits of trees for cooling urban heat islands: A meta-analysis. *Build Environ* **170**, 106606 (2020).

4. Wong, N. H., Tan, C. L., Kolokotsa, D. D. & Takebayashi, H. Greenery as a mitigation and adaptation strategy to urban heat. *Nat Rev Earth Environ* **2**, 166–171 (2021).

5. Liu, Z. *et al.* Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Build Environ* **200**, 107939 (2021).

6. Galalizadeh, S., Morrison-Saunders, A., Horwitz, P., Silberstein, R. & Blake, D. The cooling impact of urban greening: A systematic review of methodologies and data sources. *Urban For Urban Green* **95**, 128157 (2024).

7. Kumar, P. *et al.* Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. *Innovation* **5**, 100588 (2024).

8. Antoszewski, P., Świerk, D. & Krzyżaniak, M. Statistical review of quality parameters of blue-green infrastructure elements important in mitigating the effect of the urban heat island in the temperate climate (C) zone. *Int J Environ Res Public Health* **17**, 7093 (2020).

9. Lakshmisha, A., Nazar, A. F. & Nagendra, H. Nature based solutions in cities of the global South—The 'where, who and how' of implementation. *Environmental Research: Ecology* **3**, 025005 (2024).

10. Ji, L., Shu, C., Gaur, A., Wang, L. & Lacasse, M. A state-of-the-art review of studies on urban green infrastructure for thermal resilient communities. *Build Environ* **257**, 111524 (2024).

11. Aram, F., Higueras García, E., Solgi, E. & Mansournia, S. Urban green space cooling effect in cities. *Heliyon* **5**, e01339 (2019).

12. Adegun, O. B., Ikudayisi, A. E., Morakinyo, T. E. & Olusoga, O. O. Urban green infrastructure in Nigeria: A review. *Sci Afr* **14**, e01044 (2021).

13. Bowler, D. E., Buyung-Ali, L., Knight, T. M. & Pullin, A. S. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc Urban Plan* **97**, 147–155 (2010).

14. Ramakreshnan, L. & Aghamohammadi, N. The Application of Nature-Based Solutions for Urban Heat Island Mitigation in Asia: Progress, Challenges, and Recommendations. *Curr Environ Health Rep* **11**, 4–17 (2024).

15. Priya, U. K. & Senthil, R. A review of the impact of the green landscape interventions on the urban microclimate of tropical areas. *Build Environ* **205**, 108190 (2021).