**Response to Reviewer 1 :**

We sincerely appreciate your constructive comments, which have greatly improved our manuscript. We have addressed all comments point-by-point below.

1. **Q:** Abstract: The structure of the abstract needs strengthening. The beginning should clearly articulate the current gaps and limitations in quantifying vegetation phenology sensitivity to urban warming. This should be followed by a concise summary of the methodology, and finally, a systematic presentation of the results.

**R:** We thank you for this suggestion. We have completely restructured the abstract to start with the research gap, followed by concise methodology and core results.

Modified text (Abstract): "Quantifying how background temperature and aridity constrain phenological sensitivity to urban warming requires identifying critical thermal thresholds and hydrological boundaries driving spatial heterogeneity. This study assessed urban warming effects on vegetation phenology across 293 Chinese cities during 2010–2020. Urban-rural disparities (ΔSOS, ΔEOS) and temperature sensitivity ($R_{t\text{-}SOS}$, $R_{t\text{-}EOS}$) were quantified using satellite metrics. Results showed urban heat islands advanced SOS by 12.06 days and delayed EOS by 9.86 days relative to rural areas. A saturation effect was detected: phenological sensitivity to urban warming peaked at 4 °C (spring) and 6 °C (autumn), and weakened beyond LST thresholds of 12.5 °C (SOS) and 4 °C (EOS). Aridity weakened warming benefits across most aridity index (AI) ranges and reversed them within 1.4 < AI < 2.0. Combined, LST and AI explained 75.05% and 76.21% of spatial variance in SOS and EOS responses. These findings reveal nonlinear constraints of background climate on urban vegetation phenology and support climate-adaptive urban ecological planning."

2. **Q:** Line 61-63: The authors state that "While these studies offer empirical evidence, they do not sufficiently elucidate the underlying cause and its quantifiable relationship.". However, based on the stated objectives, the study primarily aims to identify a so-called saturation inflection point rather than conducting an deep exploration of the underlying mechanisms. If this is the case, the Introduction needs to more clearly highlight the specific novelty and contribution of this work.

**R:** We have revised the introduction to highlight the research gap and novelty clearly.

Modified text：

(Introduction): "While these studies offer valuable empirical evidence regarding spatial heterogeneity, the non-linear dynamics of these responses—specifically, the saturation thresholds where urban warming benefits diminish—and how background aridity modulates these inflection points remain inadequately quantified across large-scale geographic gradients. Identifying these thresholds is critical for accurately modeling and predicting urban ecosystem responses under continuous global warming scenarios."

3. **Q:** Line 126-128: The authors appear to define the urban center as Urban and a 20 km buffer zone as Rural. The reason for this specific delineation needs to be clearly explained in this section.

**R:** We sincerely thank you for pointing this out. We realize that the justification for setting the rural boundary at 20 km was not clearly presented in the Study Area section.The choice of a 20 km buffer was based on our pre-analysis of the spatial footprint of the urban heat island (UHI) effect on vegetation phenology. As illustrated in our Supplementary Materials (Figure S1 and S2), the magnitude of phenological shifts (changes in SOS and EOS) gradually decays with increasing distance from the urban center and approaches zero at approximately 15 km. Therefore, to ensure that our "Rural" reference accurately represents a true natural background unaffected by urban warming, we conservatively defined the outermost buffer zone at 20 km. Following your suggestion, we have added a clear explanation for this specific delineation in the "Study Area" section to avoid any confusion for the readers.

Modified text (2.1 Study Area): "A total of ten buffer zones were created within a radius of 20 kilometers from the city center, with each buffer zone set at a distance of 2 kilometers from the center (Figure 1).

This specific 20 km delineation was established because our preliminary analysis revealed that the urban warming footprint on phenological metrics (SOS and EOS) gradually diminishes and approaches zero at distances of 15 km and beyond (Figure 1, Figure 2). Thus, defining the outermost 20 km buffer zone as the "Rural" baseline guarantees a background environment conservatively free from urban heat island interferences. The subscript "(10)" used throughout this manuscript refers to the 10-th buffer zone located 20 km away from the urban center, and all notations in equations have been standardized to use buffer index (0 for urban center, 10 for rural reference) to avoid misinterpretation between distance and buffer number."

4. **Q:** The figure legends require more precise descriptions. For instance, Figure 3, 9, and 10 contains panels (a) and (b), yet the current legend is imprecise and fails to clearly distinguish or explain them, and also in Figure 8, please avoid errors such as obscured numerical values in Figure 8. Therefore, the authors should be carefully verify that all other figure legends are expressed clearly and rigorously. Furthermore, given the large number of figures in the main text, please consider moving some of them to the Supplementary Materials.

**R:** We sincerely appreciate the your rigorous comments on the figure legends and visualization clarity, which have greatly improved the readability and preciseness of our results presentation. We have revised the manuscript thoroughly in accordance with the comments:

(1) We have refined the legends of Figures 3, 9 and 10 to provide explicit and precise descriptions for each panel (a/b), and systematically verified all figure legends in the main text to ensure standardized and unambiguous expression.

(2) For Figure 8, we adjusted the layout positions of all statistical annotations ($R^2$) within the panels to avoid occlusion by scatter points, guaranteeing complete visibility of key statistical indicators. Meanwhile, we supplemented a concise descriptive statement in the figure legend to strengthen the interpretability of the results.

(3) All figures included in the main text illustrate the core findings of this study and are indispensable for demonstrating the saturation effect and climatic regulation mechanisms. Therefore, we retain all main-text figures without transferring them to the Supplementary Materials.

Revised Figure 8 Legend:

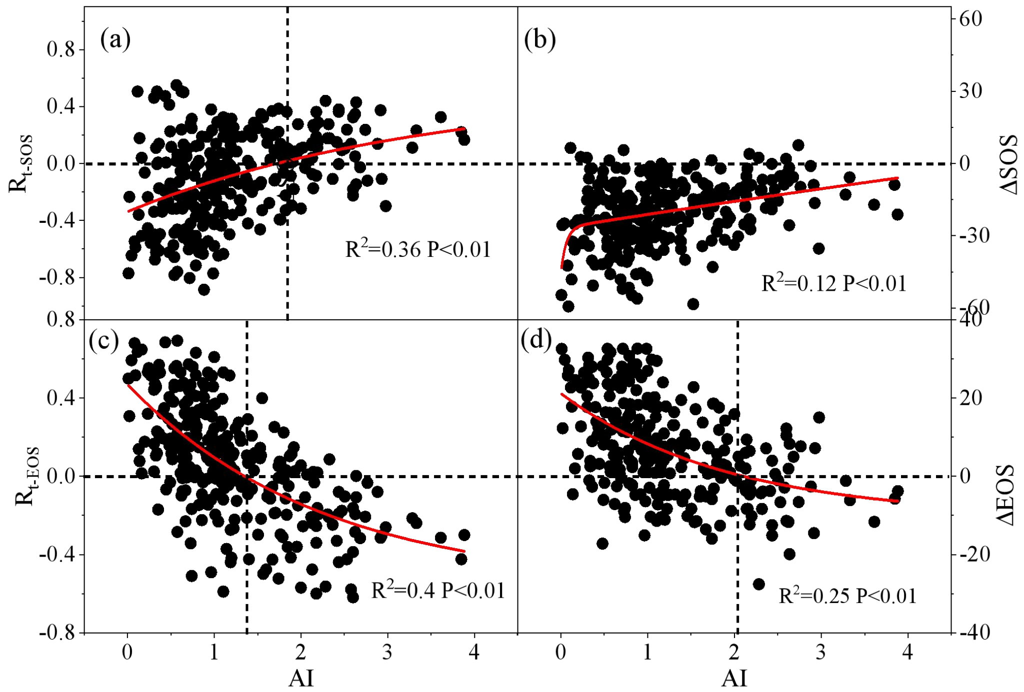


Figure 8. The AI determined phenological sensitivity and urban-rural difference. When the phenological responses were fitted to the AI, Rt-SOS and ΔSOS were positively related to AI

5. **Q:** Line 422-431: This section reads more like a summary of the Results. I recommend avoiding such redundancy. The section of Discussion should focus on analyzing and interpreting the findings rather than simply restating them.

**R:** We appreciate your critical feedback regarding the redundancy in the Discussion section. We agree that the beginning of Section 4.1 was overly descriptive and repeated many details already presented in the Results.In the revised manuscript, we have thoroughly restructured the Discussion section to minimize redundancy. We have replaced the long summary of findings with a concise synthesis of the core results and expanded the depth of our analysis. Specifically, we now focus more on the biological and ecological implications of these patterns, such as the potential impact of urban microclimates and human management practices on phenological synchronization. This change ensures that the Discussion serves its intended purpose of interpretation and synthesis rather than mere restatement.

Modified text:

"Our multi-city assessment confirms a predominant urban-rural phenological divergence across China, characterized by advanced SOS and delayed EOS within a concentrated 10-km urbanization footprint. This consistent spatial pattern validates that urban warming acts as a primary driver of phenological shifts. Beyond mere thermal forcing, this convergence across 293 cities reflects the profound impact of urban microclimates on plant life cycles. The observed 10-km threshold is particularly significant as it suggests a localized but intense ecological footprint that necessitates specialized urban greening management strategies, especially in high-density northern cities where these shifts are most pronounced."

6. **Q:** Line 433-435: The study covers a large geographical area, so the word "same

habitation" is confusing. Please clarify this point.

**R:** Response: We appreciate the your professional feedback. We agree that the term "same habitation" is imprecise and potentially confusing when applied to a large geographical study covering hundreds of cities.

Modified text:

"This consistency could be attributed to the ecological convergence of plants coexisting in shared local habitats within each city (Wang et al., 2016)."

7. **Q:** Line 455-457: There are instances of incorrect or non-idiomatic language. Please rephrase these sentences to ensure accuracy and readability. Given that similar issues appear throughout the manuscript, I strongly recommend a thorough proofreading and comprehensive language polishing of the entire text to eliminate errors and inappropriate expressions.

**R:** We carefully rectified grammatical errors, awkward phrasing, and non-idiomatic expressions throughout the manuscript, fully preserving the original meaning and content.

8. **Q:** Line 469-470, Line 476: what's the meaning of 50-51, and 46? Please carefully review the entire manuscript to avoid such mistakes.

**R:** We sincerely apologize for the redundant and meaningless typographical errors ("50-51" and "46") in the manuscript. These numbers were mistakenly inserted redundant characters. During the revision of mechanistic interpretations in response to Comment 9 (incorporating study data to support inferences), we deleted these erroneous numbers entirely, thoroughly revised the corresponding sentences with our empirical data support, and standardized the expressions and citations. We have also carefully proofread the full manuscript to eliminate similar typographical errors.

Modified text:

"While the benefits of increased temperature can be offset by the negative impacts of heat waves and excessive thermal stress (Mathur et al., 2014). Our data in Figure 5b and 5d provides direct evidence for this: when preseason temperature (T) exceeds 15℃, a decreasing trend for EOS is observed. This aligns with the intersection points identified in Figure 4c and 4d at LST=18℃, where the urban-rural phenology difference reverses, confirming that excessive heat in urban centers triggers premature leaf senescence rather than further delaying it. In fact, when T > 15 ℃, EOS tends to be reduced, with an increased sensitivity to temperature changes (Estiarte & Penuelas, 2015; Figure 5b)."

"In fact, phenological events such as bud burst could not be triggered unless forcing temperature thresholds (i.e., cumulative temperature) were fully met (Hanninen et al., 2019)."

9. **Q:** The authors provide interpretations of the results in the Discussion section, such as the possible reasons for SOS, ECOS, and drought effect. However, these mechanistic explanations mainly rely on several literature citations without sufficient supporting data from the current study, making this part of the analysis appear weak. I recommend that the authors incorporate specific data to substantiate their inferences.

**R:** We appreciate this constructive suggestion. We agree that the mechanistic discussions should be more closely integrated with our empirical findings to strengthen the analysis.

Original text 1:

"When we quantified phenological responses to temperature... Collectively, these results underscore the importance of considering non-linear and threshold-based models when predicting phenological responses under continuous environmental warming, especially in urban settings."

Modified text 1:

"When we quantified phenological responses to temperature across the climatic gradient, clear logistic trends were observed for both SOS and EOS (Figure 5). Consistent with this logistic trajectory, we observed that in urban areas, the growth rate for SOS/EOS began to plateau when temperatures exceeded 4℃/6℃, respectively (Figure 5)... As illustrated by the first-order derivatives in Figure 5c and 5d, the phenological sensitivity to temperature does not increase linearly, but peaks at T=4℃ for SOS and T=6℃ for EOS before rapidly declining. Specifically, the stabilization of urban SOS at 101.3 days and rural SOS at 129.7 days when LST is low (Figure 4a) further demonstrates that plants reach a mandatory physiological threshold that cannot be bypassed by additional thermal forcing. Collectively, these results highlight that threshold-based nonlinear models rather than simple linear relationships are more suitable for predicting phenological responses under scenarios of continuous environmental warming, especially in urban settings. Conceptually, these saturation thresholds challenge the traditional linear paradigm of 'warming-driven phenological advancement.' By identifying explicit thermal boundaries, our framework establishes that the physiological capacity of urban vegetation to capitalize on UHI warming is strictly finite."

Original text 2:

"Typically... vegetation needs to undergo a period of exposure to low chilling temperatures... when ambient temperatures are relatively high, these chilling requirements may not be met..."

Modified text 2:

"Typically, vegetation needs to undergo a period of exposure to low chilling temperatures. This mechanism is consistent with our spatial observations in Figure 2a, where cities in lower latitudes (warmer regions) exhibit significantly smaller ΔSOS values. This suggests that in these warmer territories, the higher background LST may fail to satisfy the necessary chilling requirements, leading to the diminished phenological sensitivity we quantified in Figure 3."

Original text 3:

"While the benefits of increased temperature can be offset by the negative impact of heat waves and droughts that result from higher LST. These passive feedback loops can cause widespread leaf senescence..."

Modified text 3:

"While the benefits of increased temperature can be offset by the negative impact of heat waves. Our data in Figure 5b and 5d provides direct evidence for this: when preseason temperature (T) exceeds 15℃, a decreasing trend for EOS is observed. This aligns with the intersection points identified in Figure 4c and 4d at LST=18℃, where the urban-rural phenology difference reverses, confirming that excessive heat in urban centers triggers premature leaf senescence rather than further delaying it."

Original text 4:

"Spatially, the coastal cities experienced more benefits from the urban warming (Figure 2)... AI explained 10.14% and 17.33% variation dependently for the spatial distribution of ΔSOS and ΔEOS."

Modified text 4::

"Spatially, the coastal cities experienced more benefits from the urban warming. Our statistical decomposition in Figure 10 further elucidates this aridity-driven modulation, showing that AI and LST together explain over 75% of the variance in ΔSOS and ΔEOS. Notably, the fact that AI explains 17.33% of the variation in ΔEOS (Figure 10c) supports our inference that water availability is a critical limiting factor in autumn. This is further substantiated by the positive correlation between ΔSOS and AI in Figure 8b, which quantifies how increasing aridity progressively offsets the advanced green-up typically induced by urban warming."

10. **Q:**Line 484-488: This section also reads more like a description of the results and lacks substantive discussion. The authors should focus on interpreting the findings, exploring their implications, and comparing them with existing literature. Similarly, Line 496-500 merely repeat the presentation of results without offering in-depth analysis or discussion.

**R:** We appreciate your comment regarding the lack of substantive discussion in these sections. We have revised both paragraphs to move beyond descriptive summaries.

Modified text (Line 484-488) "Beyond thermal controls alone, our findings regarding the aridity-driven modulation of phenological responses provide a critical geographic context that complements previous observations. While earlier studies primarily emphasized thermal forcing as the dominant driver of urban phenology (Meng et al., 2020), our results demonstrate AI acts as a significant 'environmental filter' that can override or even reverse warming benefits. As shown in Figure 8 and 10, the high explanatory power of AI (up to 17.33% for ΔEOS) suggests that in water-limited regions of Northern and Western China, the physiological stress induced by drought prevents plants from utilizing the additional heat provided by the Urban Heat Island (UHI) effect. This phenomenon is consistent with the 'resource limitation' theory, where plant development is constrained by the most limiting resource (water), regardless of optimal temperatures. Compared to coastal cities where water is abundant, the weakened warming benefits in arid inland cities highlight the need for regionally-differentiated urban irrigation strategies to maintain ecological productivity."

Modified text (Line 496-500): "In addition to background temperature (LST), the aridity index (AI) also drives significant spatial variation in urban-rural phenological disparities (ΔSOS, ΔEOS). Spatially, the coastal cities experienced more benefits from the urban warming (Figure 2). Our statistical decomposition in Figure 10 further elucidates this aridity-driven modulation, showing that AI and LST together explain over 75% of the variance in ΔSOS and ΔEOS. Notably, the fact that AI explains 17.33% of the variation in ΔEOS (Figure 10c) supports our inference that water availability is a critical limiting factor in autumn. This is further substantiated by the positive correlation between ΔSOS and AI in Figure 8b, which quantifies how increasing aridity progressively offsets the advanced green-up typically induced by urban warming."

11. **Q:** In Section 4.4, the authors aim to discuss the responses of phenology in different vegetation types to temperature changes and drought. While this is a valuable point, as a standalone discussion section, it appears abrupt given the study's objectives and the introduction. There is virtually no prior groundwork laid for this specific topic earlier in the manuscript. I recommend that the authors reconsider the coherence of this research point throughout the paper, ensuring better alignment between the introduction, objectives, and discussion, and provide a more in-depth exploration of these findings.

**R:** We sincerely thank you for this constructive criticism. We agree that the analysis of different vegetation types in Section 4.4 lacked sufficient grounding in the earlier sections of the manuscript, making it appear disconnected from the primary objectives. To address this and ensure logical coherence throughout the paper, we have made the following structural modifications:

In the Introduction: Added theoretical foreshadowing for vegetation-type differences in the Introduction, linking them to the core themes of saturation effect and aridity modulation, thus ensuring tight alignment between the Introduction, research objectives, and Section 4.4.

Modified text (Line 70):

"Furthermore, phenological sensitivity to environmental drivers is species-specific and modulated by functional traits. Broad-leaf and coniferous species show divergent responses to warming and drought due to differences in leaf morphology and hydraulic architecture (Zheng et al., 2022). However, whether the 'saturation effect' and 'aridity-driven inhibition' operate consistently across urban vegetation types remains unclear."

In Section 4.4: We have significantly expanded the discussion to better interpret our findings from an eco-physiological perspective, linking the observed sensitivity differences to specific plant traits.

Modified text (Section 4.4):

"The phenological response to LST and AI varies significantly across vegetation types, reflecting the influence of distinct ecological strategies. Our results (Figure 6 and 9) demonstrate that Shrublands are the most sensitive to both warming and aridity, likely due to their opportunistic resource utilization strategy and higher leaf turnover rates (Xiong et al., 2024). In contrast, Coniferous Forests exhibited a muted response to both drivers (Malla et al., 2023). While our analysis relies on broad land-cover categories and does not directly measure species-specific functional traits, these discrepancies likely reflect generalized divergent ecological strategies among the vegetation groups.

This insensitivity is substantiated by our AI-sensitivity analysis (Figure 9a), suggesting that the conservative hydraulic traits of conifers—such as needle morphology and lower stomatal conductance (Sperry et al., 2002; McAdam, 2013) —act as a buffer against the "aridity-driven inhibition" that more severely affects broad-leaf species. Based on generalized ecological principles, this might be associated with typical drought-resistant adaptations found in many conifers (e.g., needle morphology and stricter stomatal control), which could limit the potential positive impact of warming on their phenology. In contrast, the heightened sensitivity of shrublands observed in our dataset aligns with literature suggesting more opportunistic resource utilization strategies in shrubs (Xiong et al., 2024).

By considering these functional differences, our study provides a more nuanced understanding of urban ecosystem resilience, suggesting that urban greening programs should prioritize drought-resistant coniferous or mixed forest structures in regions where the warming-saturation effect is most pronounced. However, we note that these functional interpretations remain broad generalizations; future studies incorporating field-based, species-level trait measurements are required to mechanistically validate these large-scale categorical patterns. Recognizing these trait-mediated responses is a crucial conceptual step for urban forestry. It indicates that building climate-resilient urban ecosystems requires shifting from generic greening to deploying specific functional traits—such as the conservative hydraulic strategies of conifers—to buffer against the coupled heat-aridity saturation effects."