

# Global hydroclimatic constraints on greening transitions for urban cooling

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## Article

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# Global hydroclimatic constraints on greening transitions for urban cooling

## Abstract

Urban green spaces can cool cities, yet the greenness level at which cooling begins remains unresolved. We analyse >84,000 satellite observations from 711 cities worldwide to identify hydroclimate-dependent greening transitions for urban cooling. Using nonlinear mixed-effects models grounded in surface energy balance theory, we define the cooling onset (NDVI-ZC) as the greenness level at which vegetation shifts from neutral or warming effects on land surface temperature to net cooling along a smooth response curve. NDVI-ZCs vary systematically across hydroclimatic regimes, occurring at lower greenness in dry regimes and higher greenness in seasonally dry regimes, while wet regimes show persistent cooling across the observed greenness range. We demonstrate that urban cooling is constrained by hydroclimate-specific greening transitions, below which vegetation fails to deliver net surface cooling. Beyond onset, cooling responses are nonlinear and regime-dependent, indicating that effective urban cooling does not scale proportionally with vegetation cover.

## Introduction

As cities expand and the planet warms, extreme urban heat events are increasingly frequent, intense and persistent<sup>1,2</sup>. Urban green spaces (UGS), including trees, shrubs, grasslands, wetlands and mangroves, can moderate these extremes through shading, evapotranspiration and local microclimatic regulation<sup>3,4</sup>. While a negative relationship between UGS greenness and land surface temperature (LST) is widely documented<sup>5-7</sup>, the magnitude and reliability of vegetation-driven cooling vary substantially across climatic zones<sup>8-10</sup>, rainfall regimes<sup>11,12</sup> and urban configurations<sup>13-15</sup>. This variability has generated inconsistent recommendations for how much greening is needed to reduce urban heat and whether cooling benefits scale universally across regions<sup>16,17</sup>.

A major source of global variability in UGS cooling arises from hydroclimatic constraints that regulate the partitioning of net radiation ( $R_n$ ) into sensible heat flux ( $H$ ) and latent heat flux ( $LE$ ). Vegetation cools the land surface by shifting energy from  $H$  to  $LE$  via transpiration and by reducing heat storage in impervious substrates<sup>18-20</sup>. In water-limited dry climates,  $LE$  is constrained by soil moisture and low humidity, so even modest increases in greenness can substantially increase evaporative fraction ( $EF = LE / (H + LE)$ ) and reduce LST<sup>21-24</sup>. In contrast, in energy-limited humid or cold climates where moisture is abundant,  $LE$  is constrained primarily by available radiation, and vegetation must reach higher structural density before transpiration and shading generate detectable cooling effects<sup>25</sup>.

Interacting physical controls on evaporative energy exchange imply that urban greening should exhibit nonlinear, hydroclimate-dependent transitions in cooling effectiveness (Fig. 1). That is, below a certain greenness level, vegetation exerts little to no cooling, or even net warming effects, while above this transition, transpiration and shading dominate, producing net surface cooling. Normalized difference vegetation index (NDVI) is an effective proxy for these dynamics because it reflects canopy density and is strongly correlated with leaf area index (LAI) and absorbed photosynthetically active radiation, but its coupling to  $LE$  is nonlinear<sup>26-28</sup>. NDVI saturates at moderate to high canopy densities, while aerodynamic and stomatal constraints introduce threshold-like increases in canopy conductance<sup>24,29</sup>. Together, these processes predict that LST responds to greenness through smooth, nonlinear responses with climate-specific transition points indicating the onset and strength of vegetation-driven cooling rather than abrupt tipping points (Fig. 1).

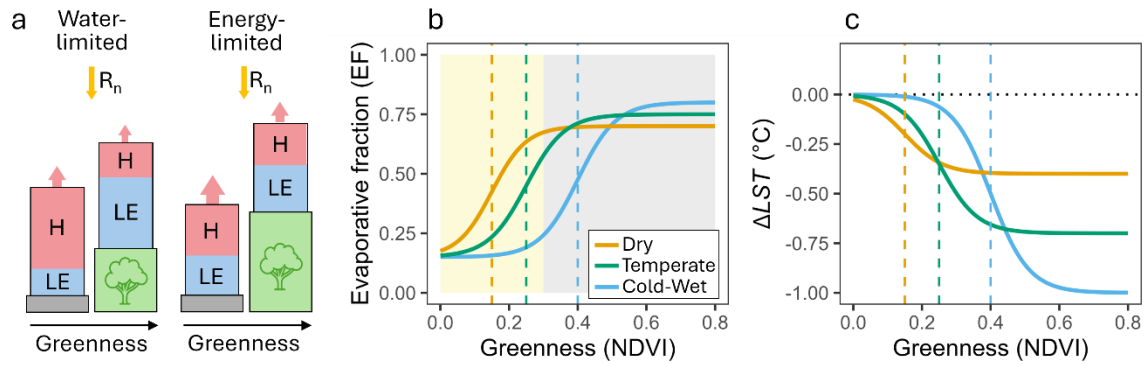


**Figure 1 | Hydroclimatic controls on greening transitions for urban cooling.** a) Conceptual surface energy balance illustrating how vegetation greenness shifts net radiation ( $R_n$ ) partitioning from sensible heat flux (H) to latent heat flux (LE) under water-limited (dry) and energy-limited (cold-wet) regimes. In water-limited climates, modest increases in greenness (NDVI) rapidly enhance LE and reduce H, whereas in energy-limited climates, LE responds only once vegetation reaches sufficient density. b) Theoretical expectation that evaporative fraction ( $EF = LE / (H + LE)$ ) will increase nonlinearly with NDVI, with early rises in dry climates, intermediate responses in temperate climates, and delayed transitions in cold-wet climates. Vertical dashed lines indicate hydroclimatic regime-specific greenness transition zones along the NDVI gradient where EF begins to increase more rapidly. Shaded areas indicate water-limited (yellow) and energy-limited (grey) climates, respectively. c) Corresponding conceptual NDVI- $\Delta LST$  relationship, showing earlier but weaker cooling responses in water-limited climates and delayed but stronger cooling responses in energy-limited climates. The dashed lines illustrate smooth, climate-specific transition behaviour along continuous response curves rather than abrupt tipping points.

Despite strong theoretical support for climate-dependent greening transitions, no study has quantified, at the global scale, the greenness level at which urban vegetation is expected to begin delivering net surface cooling, nor how these transition points vary across hydroclimatic regimes and vegetation structures. Existing global analyses have primarily focused on the magnitude of cooling once vegetation is present<sup>8,9,30,31</sup>, and emerging evidence further suggests that urban vegetation can even shift from cooling to warming as aridity increases<sup>32</sup>. However, far less attention has been given to identifying the greenness level at which effective cooling first emerges along the vegetation gradient. This gap limits the ability of cities to design climate-adaptive greening strategies that align UGS interventions with the biophysical constraints on cooling effectiveness.

Here, we integrate satellite-derived greenness-temperature observations from 711 cities worldwide (Supplementary Table S1) to quantify climate-specific greening transitions for urban cooling. Cities were near-evenly distributed across major Köppen–Geiger climate zones (arid, cold, temperate and tropical) to ensure balanced climatic representation (Fig. 2a; Supplementary Fig. S1). Across cities,  $\Delta LST$  ( $LST_{UGS} - LST_{grey}$ ; °C) were calculated for >84,000 spatially and temporally matched NDVI and LST observations (Supplementary Fig. S2). Using nonlinear mixed-effects models grounded in surface energy balance theory, we identify the NDVI zero-crossing (NDVI-ZC) to mark the expected onset of net surface cooling, the greenness level associated with maximum cooling efficiency under extreme heat (NDVI-opt), and the role of vegetation structure in modulating post-transition cooling magnitude. Together, this approach provides a mechanistic, climate-adaptive framework for understanding when and where urban greening delivers meaningful thermal benefits.

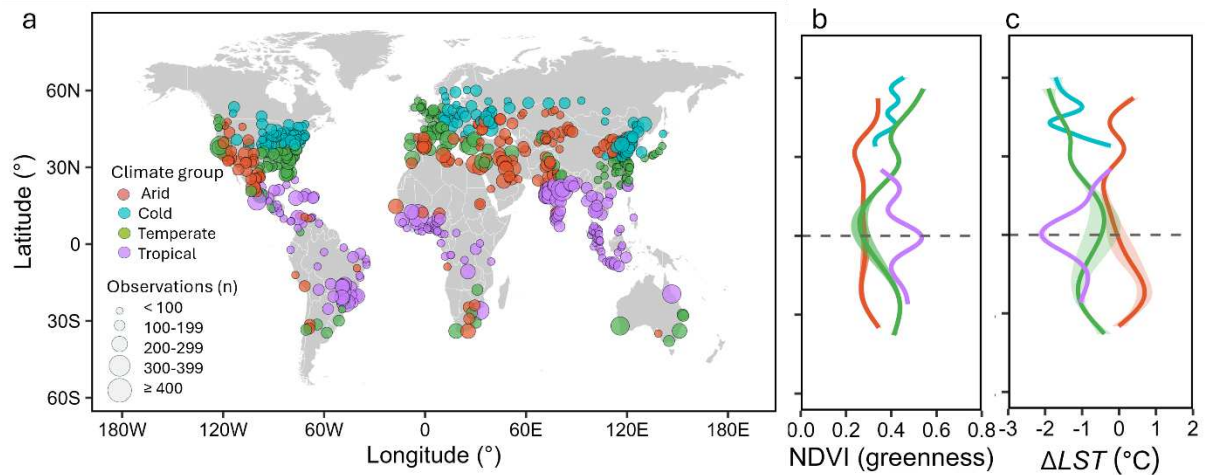


**Figure 2 | Global distribution of urban sites and latitudinal trends of greenness and cooling across climate zones.** **a)** 711 urban sites are approximately evenly distributed across the Köppen-Geiger climate zones. Point colours indicate climate zones (arid, cold, temperate and tropical), and point sizes represent the number of observations per site ( $n = 84,290$ ). See Supplementary Fig. S1 for climate sub-classification and distribution. Latitudinal trends of **b)** vegetation greenness (NDVI) and **c)** corresponding cooling intensity ( $\Delta LST$ ; difference in land surface temperature between urban green and grey spaces,  $^{\circ}C$ ). In panels b-c, solid lines show smoothed latitudinal trends for each climate zone, with shaded envelopes indicating uncertainty around the smooths'. Horizontal dashed lines mark the equator ( $0^{\circ}$ ).

## Results

### Global Variability in NDVI-LST Responses

Across this global sample, NDVI and  $\Delta LST$  exhibited coherent contrasts among climate zones, alongside substantial within-group variability (Fig. 2b-c). This combination of structured climatic differences and internal heterogeneity indicates that linear greening-cooling relationships are unlikely to hold across cities, motivating the use of nonlinear, climate- and hydroclimate-structured modelling approaches. Globally, the cooling effect of UGS was  $\Delta LST = -0.78$  (median; IQR -1.99 to  $0.30^{\circ}C$ ; Supplementary Fig. S3), with the strongest UGS cooling effects observed in wet regime, cold and temperate climates, hydric UGS type, and higher latitude cities ( $\geq 60^{\circ}N$ ) with median  $\Delta LST$  ranging from  $-3.10$  to  $-1.08^{\circ}C$  (Supplementary Table S2; Supplementary Fig. S4).

Across 711 cities, NDVI-LST observation clusters within distinct hydroclimatic envelopes, reflecting climate-dependent constraints on the conditions under which greenness produces net surface cooling (Figure 3; Supplementary Fig. S5). Temperate and wet climates occupy broad NDVI-LST envelopes with cooling predominantly occurring at moderate to high greenness, whereas arid systems exhibit narrower envelopes, with cooling weaker and largely confined to high NDVI conditions (Fig. 3). Seasonally dry climates show intermediate behaviour, with cooling concentrated at mid NDVI and strengthening toward warmer background temperatures (Fig. 3). Across tropical climates, NDVI-LST envelopes are relatively narrow but internally consistent, with cooling occurring across a broad NDVI range at higher background temperatures (Figure 3). Importantly, these envelopes reveal broad transition zones rather than abrupt boundaries, indicating that vegetation-driven cooling emerges gradually along the greenness gradient rather than at a single sharp tipping point.

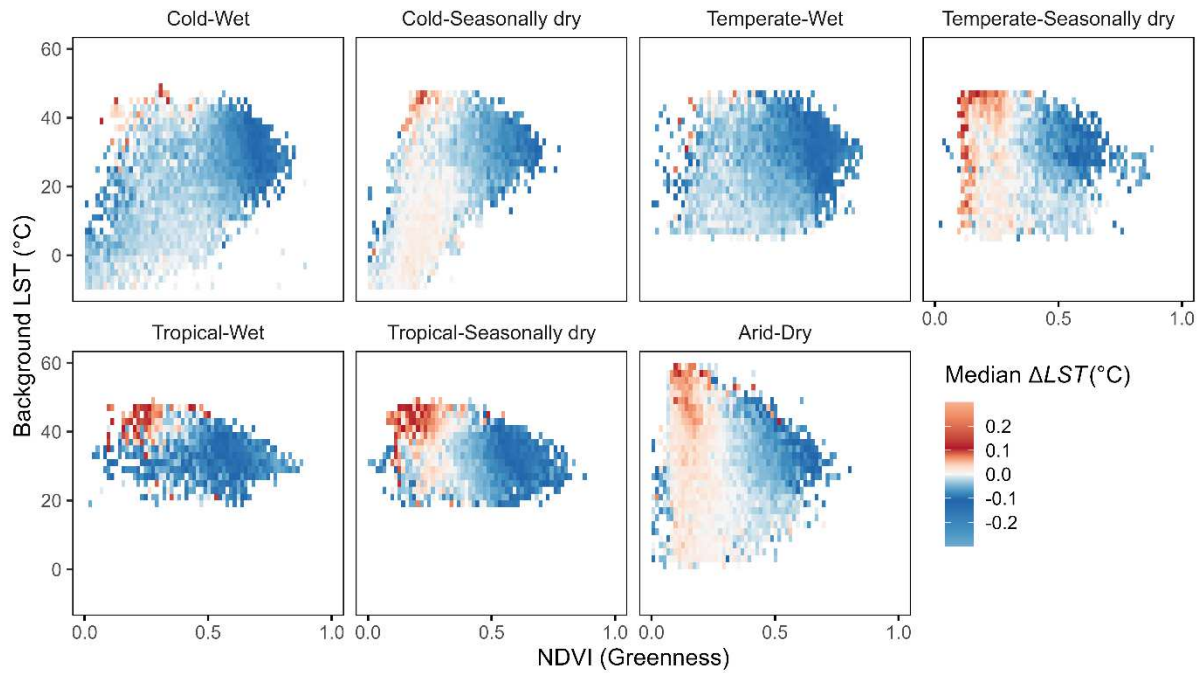


**Figure 3 | Hydroclimatic envelopes for vegetation-driven cooling across global cities.** Distribution of observations across NDVI and background land surface temperature (LST; °C) is shown for each hydroclimatic group (climate zone × precipitation regime) across 711 cities globally. Coloured tiles represent median  $\Delta LST$  within each NDVI-LST bin, with blue and red colours, indicating cooling and warming, respectively.

### Hydroclimate-Dependent Cooling Transitions

To characterise nonlinear NDVI- $\Delta LST$  relationships across climate and precipitation regimes, we analyse 84,290 spatially and temporally matched NDVI and LST observations using a combination of LMMs and GAMMs (see Methods). LMMs were initially used to identify the dominant drivers of UGS cooling. Across all model specifications, vegetation greenness (NDVI) emerged as the strongest predictor of  $\Delta LST$ . Incorporating hydroclimate regime, climate zone and UGS type substantially improved model performance compared to NDVI-only models ( $\Delta AIC_{df} \leq -45$ ;  $\Delta R^2_m \sim 0.02-0.10$ ; Supplementary Tables S3). The final LMM retained NDVI, UGS type, precipitation regime and climate zone as fixed effects, with latitude as a spatial random effect (Supplementary Tables S4; Supplementary Fig. S6). Longitude was additionally retained to account for residual spatial structure and improve stability in subsequent GAMM analyses.

While LMMs indicated a consistent increase in cooling with greenness across cities, their linear structure could not capture the curvature expected from hydroclimatic constraints on surface energy partitioning. We therefore examined NDVI- $\Delta LST$  relationships using GAMMs with hydroclimate-specific smooths of NDVI. GAMMs substantially improved model fit (adjusted  $R^2 \sim 0.44$ ; Supplementary Tables S5-S8; Supplementary Figs. S7-S9) and reproduced the unimodal response shapes predicted by surface energy theory (Fig. 1). Specifically, across hydroclimatic groups, cooling was weak or slightly positive at low NDVI, intensified once vegetation reached a hydroclimate-dependent greenness level and saturated at high NDVI (Fig. 4). Model diagnostics indicated low concavity and stable smooth terms across alternative temporal windows, vegetation classifications, NDVI products and spatial scales (Supplementary Figs. S10-S13).

From the GAMM-derived NDVI- $\Delta LST$  curves, we identified two interpretable greenness metrics. The cooling onset (NDVI-ZC) was defined as the NDVI value at which the predicted  $\Delta LST$  crosses zero, representing the greenness level at which the expected LST response transitions from warming or

neutral to net surface cooling along a smooth nonlinear curve. Under extreme heat conditions (here, the hottest 10% of observations based on background LST), we additionally defined the cooling optimum (NDVI-opt) as the NDVI value at which predicted  $\Delta$ LST reaches its most negative value, indicating maximum cooling efficiency (Supplementary Fig. S14-S15).

GAMM predictions revealed systematic variation in NDVI-ZC across precipitation regimes (Fig. 4). Cooling initiated at lower greenness levels in dry regimes (NDVI-ZC  $\sim$  0.29) than in seasonally dry regimes (NDVI-ZC  $\sim$  0.31), whereas wet regimes exhibited persistent cooling across the full observed NDVI range with no zero crossings (Fig. 4a; Supplementary Table 9). Under extreme heat conditions, the NDVI- $\Delta$ LST relationship transitioned from cooling onset to a pronounced cooling optimum, with NDVI-opt values of approximately 0.52, 0.57 and 0.59 for seasonally dry, dry and wet regimes, respectively (Supplementary Fig. S16).

The magnitude of cooling beyond NDVI-ZC also varied strongly across regimes. Seasonally dry and wet regimes exhibited substantially stronger post-transition cooling than dry regimes (Fig. 4b), reflected in divergence of predicted  $\Delta$ LST distributions at moderate to high NDVI (Fig. 4c). Under extreme heat, upward shifts in both NDVI-ZC and NDVI-opt indicate that higher greenness is required to initiate and maximise cooling relative to baseline conditions (Supplementary Figs. S17-S18). Although the precipitation regime explained large differences in cooling onset and optimum, substantial within-regime variability in cooling magnitude remained.

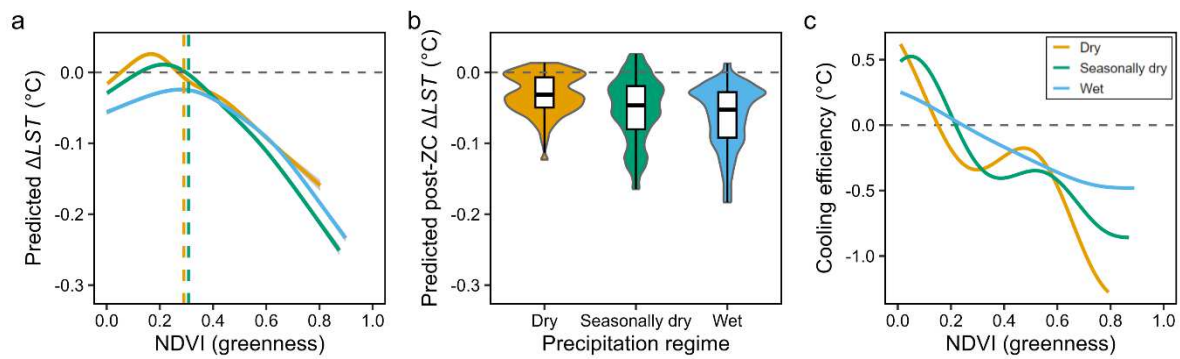


**Figure 4 | Precipitation-driven variation in greening transitions and cooling efficiency.** **a)** Predicted change in  $\Delta$ LST (difference in land surface temperature between urban green and grey spaces; °C) as a function of vegetation greenness (NDVI) across dry, seasonally dry and wet precipitation regimes. Curves represent smoothed trends of  $\Delta$ LST values predicted by the fitted GAMM across NDVI within each precipitation regime. Shaded ribbons indicate 95% confidence intervals of the secondary smoothing applied to model predictions. Vertical dashed lines denote the median NDVI zero-crossing (NDVI-ZC) for each regime, the greenness level at which  $\Delta$ LST transitions from warming or neutral to net surface cooling. NDVI-ZCs for dry and seasonally dry are only presented as wet regimes exhibited persistent cooling across the full observed NDVI range. **b)** Violin plots with embedded boxplots show distributions of predicted  $\Delta$ LST at NDVI values above the zero-crossing, presenting post-onset cooling for each precipitation regime. **c)** Cooling efficiency (°C per NDVI unit) is shown across precipitation regimes, with curves representing the derivative of GAMM-predicted NDVI- $\Delta$ LST to quantify the marginal cooling benefit of additional greenness. Horizontal dashed lines indicate predicted  $\Delta$ LST = 0 °C and cooling efficiency = 0 °C in panels a-b) and c), respectively.

### Structural Controls on Cooling Efficiency

Vegetation greenness explained the largest share of model deviance in  $\Delta$ LST (> 50%), with UGS type contributing a substantial secondary effect (Fig. 5a). Structural differences among UGS types produced distinct NDVI- $\Delta$ LST response patterns (Fig. 5b; Supplementary Fig. S19), with cooling intensities differing markedly between all observations and post NDVI-opt across UGS types (Fig. 5c).

Biophysical drivers underlying this residual variability were examined using the partial effects from the full GAMM under an illustrative hydroclimatic conditions (temperate-wet), showing that vegetation structure produces distinct NDVI- $\Delta$ LST response shapes even when hydroclimate is held constant (Supplementary Fig. S20). Cooling efficiency curves further revealed that UGS types differ not only in the magnitude of marginal cooling gained per unit increase in greenness, but also in how cooling efficiency changes with increasing NDVI (Fig. 5d; Supplementary Fig. S21). For instance, hydric systems exhibit nonlinear responses with relatively low cooling efficiency at low NDVI, whereas woody systems maintain a comparatively stable efficiency across moderate to high NDVI. Vegetation greenness and structural characteristics are thus a dominant control on both the onset and magnitude of cooling, acting independently of hydroclimate.

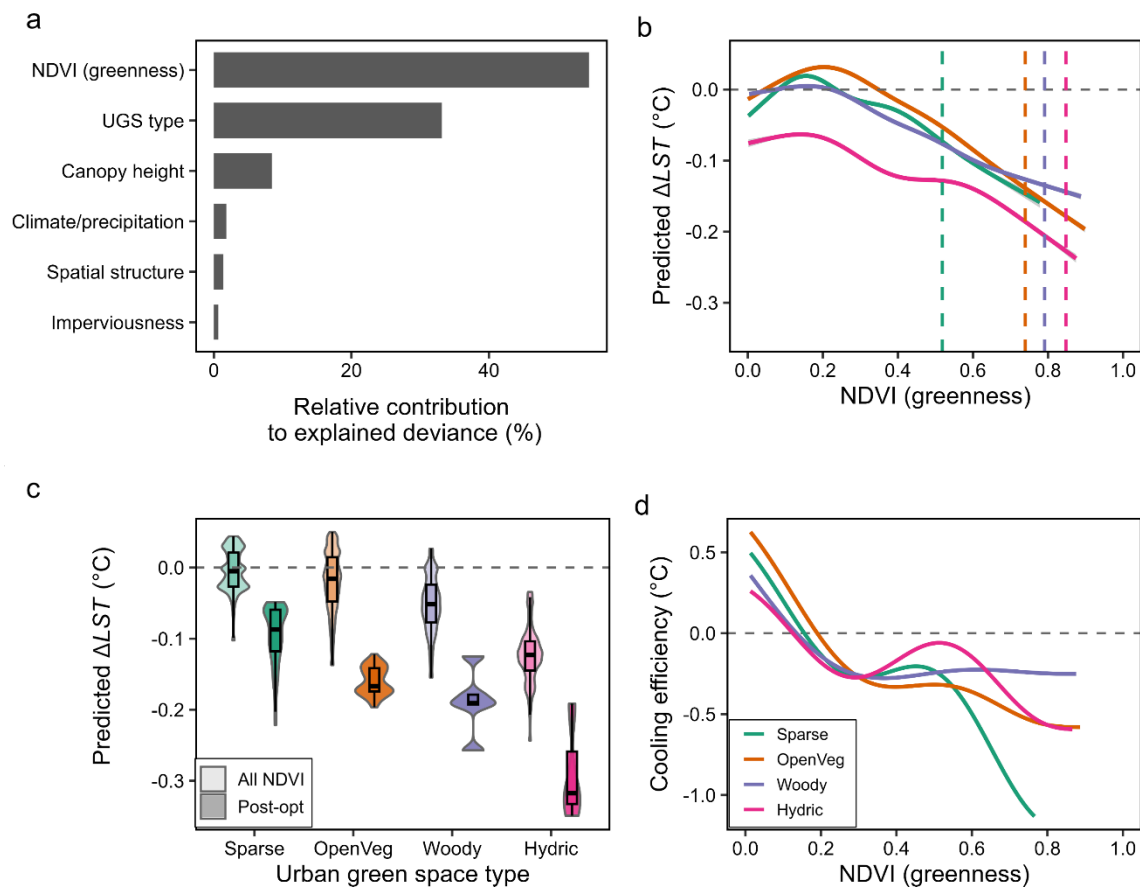


**Figure 5 | Structural controls on cooling optimum and efficiency across UGS types.** **a)** Relative contribution of biophysical and environmental drivers to explained deviance in  $\Delta$ LST (difference in land surface temperature between urban green and grey spaces,  $^{\circ}$ C), quantified by sequentially refitting the full GAMM while excluding one term at a time. **b)** Curves represent smoothed trends of  $\Delta$ LST values predicted by the fitted GAMM across NDVI within each urban green space type (UGS; sparse vegetation, open vegetation, woody and hydric type). Shaded ribbons indicate 95% confidence intervals of the secondary smoothing applied to model predictions. Vertical dashed lines denote the cooling optimum (NDVI-opt) identified under extreme heat conditions (the hottest 10% of observations based on background LST). **c)** Distributions of predicted  $\Delta$ LST across UGS types. Violin plots with embedded boxplots summarise predicted  $\Delta$ LST for all observations (lighter colours) and for observations exceeding the UGS-specific NDVI-opt (darker colours), representing post-optimum cooling. **d)** Cooling efficiency ( $^{\circ}$ C per NDVI unit) derived from the first derivative of the NDVI- $\Delta$ LST smooths, quantifying the marginal cooling gain associated with additional greenness across UGS type. Horizontal dashed lines indicate predicted  $\Delta$ LST = 0  $^{\circ}$ C and cooling efficiency = 0  $^{\circ}$ C in panels b-c) and d), respectively.

## Discussion

Our global analysis shows that UGS cooling capacity is neither uniform nor linear but emerges from the interplay among ecological, climate and structural constraints. While surface energy balance theory predicts such interacting controls (Fig. 1), their global expression across real urban systems has not previously been quantified. Previous global analyses quantified the magnitude and spatial inequality of cooling once vegetation is present. By comparison, our analysis identifies the greenness level required for cooling to emerge in the first place. Across 711 cities with near-equal representation of four major climate zones (Fig. 2), we identify distinct NDVI-LST envelopes that capture the biophysical space across which cooling responses vary (Fig. 3). By resolving these envelopes globally, we show that urban cooling responses are bounded by hydroclimatic constraints rather than scaling proportionally with greenness. The greening transition points for cooling onset (NDVI-ZC) and cooling optimum (NDVI-opt) reveal clear hydroclimatic limits on vegetation-mediated cooling, demonstrating that urban LST reduction depends jointly on hydroclimatic conditions and vegetation greenness (Figs. 4). Across all cities, greenness (NDVI) remains the dominant control on urban cooling, with UGS type exerting an important secondary influence, reflecting the role of vegetation structure in modulating the magnitude and efficiency of cooling once surface temperature reduction has emerged (Fig. 5).

Greening transitions arise from surface energy partitioning (Fig. 1). Vegetation cools the surrounding surface only once it can divert  $R_n$  from  $H$  to  $LE$ , but this transition is constrained by the local hydroclimatic conditions. In dry regimes,  $LE$  is moisture-limited at low NDVI, therefore, even modest increases in leaf area can rapidly enhance canopy conductance and soil evaporation, increasing  $EF$  and triggering earlier cooling onset<sup>33–35</sup>. In contrast, humid and cold-wet regimes are primarily energy-limited. Despite abundant moisture,  $LE$  cannot increase until vegetation becomes sufficiently dense to overcome aerodynamic, radiative and stomatal constraints<sup>36,37</sup>. Consistent with these physical controls, greening does not yield continuous cooling; rather, it generates smooth, nonlinear transitions in surface energy partitioning. Importantly, NDVI-ZC does not represent an abrupt ecological tipping point, but rather a probabilistic transition along a continuous surface energy response curve. The cooling onset (NDVI-ZC) marks the point at which vegetation can effectively redirect net radiation from  $H$  to  $LE$ , whereas the cooling optimum (NDVI-opt) under extreme heat conditions indicates saturation in the marginal cooling benefit of additional greenness (Figs. 4–5; Supplementary Figs. S17–S18). In wet regimes, the absence of detectable NDVI-ZCs indicates persistent cooling across the full range of observed NDVI, with thermal benefits governed primarily by energy availability rather than moisture constraints<sup>38</sup>. This implies that in energy-limited regimes, even sparse vegetation contributes sufficient evapotranspiration to offset sensible heat.

Climate-specific efficiency limits have been widely recognised as defining when additional greening yields diminishing thermal returns, yet their mechanistic basis and climatic generality have remained unclear<sup>38,39</sup>. By identifying greening transition points for both NDVI-ZC and NDVI-opt across hydroclimatic regimes, our results provide a unifying, process-based explanation rooted in surface energy partitioning, independent of green space size, spatial configuration or urban form. These landscape-scale transitions align with power-law cooling dynamics previously reported in patch-scale studies<sup>40–43</sup>, extending the concept of green area transitions from individual parks to continuous urban landscapes.

Importantly, these transitions are not fixed. Upward shifts in both NDVI-ZC and NDVI-opt under hotter conditions suggest that heatwaves and climate warming will require denser vegetation to initiate and maximise cooling<sup>44</sup>. Even after cooling onset, the magnitude of realised cooling varies markedly with hydroclimate, with seasonally dry and wet regimes exhibiting substantially stronger

post-transition reductions in  $\Delta$ LST than arid systems, where cooling remains constrained even at high NDVI (Fig. 4; Supplementary Figs. S17-S18). This duality helps reconcile contradictions in the literature, where vegetation cooling is reported as both strong<sup>45,46</sup> and weak<sup>47,48</sup> in dry regimes, and demonstrates that urban cooling benefits are inherently nonlinear and climate-contingent. Apparent inconsistencies arise because greening effectiveness depends not only on vegetation presence, but on whether hydroclimatic conditions allow greenness to translate into evaporative cooling. These findings caution against assuming proportional cooling gains with increasing vegetation cover and instead highlight the need for greening strategies aligned with local hydroclimatic limits<sup>46,49</sup>.

Vegetation greenness (NDVI) underscores the fundamental role of vegetation density in regulating surface energy exchange<sup>50</sup>. Vegetation structure introduces important variation in how efficiently greenness is translated into LE and surface temperature reduction<sup>51</sup> (Fig 5a). Together, these findings indicate that while greenness defines the overall cooling potential, structural characteristics govern the rate and magnitude of cooling gains along the NDVI gradient. This distinction has important implications for urban climate adaptation and design. In dry cities, structurally efficient vegetation such as wood canopies, combined with water-sensitive designs that sustain evapotranspiration<sup>52,53</sup>, is likely to maximise cooling benefits. Seasonally dry climates emerge as particularly high-leverage contexts, combining moderate greenness transitions with strong post-transition cooling<sup>54</sup>, whereas humid cities require dense, vertically complex canopies to achieve thermal benefits<sup>55</sup>.

Our results demonstrate that variability in urban cooling emerges from interacting biophysical limits imposed by hydroclimate, vegetation greenness and vegetation structure. Hydroclimatic controls determine the greenness level at which cooling begins and shape its sensitivity to extreme heat. Once cooling is initiated, the magnitude and efficiency of LST reduction are governed primarily by the level of greenness and the structural characteristics of the vegetation. This framework explains why UGS cooling responses vary widely among cities and why linear greening targets often fail to deliver consistent benefits. By resolving where, when and under what hydroclimatic conditions urban greening begins to cool the surface, this study advances a scalable, mechanistic basis for climate-adaptive urban greening. Effective cooling strategies will depend not simply on increasing vegetation cover, but on aligning greening interventions with local hydroclimatic regimes, vegetation structure and heat-risk profiles. Such alignment offers a pathway toward more resilient, equitable and thermally effective cities under ongoing global warming.

## Methods

**Study area** We used the 2018 Global Urban Boundary (GUB) data at 30 m resolution<sup>56</sup> and restricted the urban areas to sizes between 60 km<sup>2</sup> and 3,000 km<sup>2</sup> to ensure sufficient sampling of urban pixels in satellite observations and to minimise scale-dependent modelling bias associated with underrepresented small cities and the extreme spatial heterogeneity of mega-cities. We randomly selected 800 cities using stratified sampling, evenly distributed across four major Köppen-Geiger climate zones (200 sites per zone: arid, cold, temperate and tropical). For each selected city, we employed the 2021 ESA WorldCover Map at 10 m resolution<sup>57</sup> to delineate built-up areas that mask distinct types of urban green spaces (UGS), including trees, shrubs, grass, crops, sparse vegetation, wetlands, and mangroves. To ensure comparability across climate zones, LST and NDVI values were standardised within each climate zone, and observations were downsampled to achieve approximately balanced sample sizes across zones. The final dataset comprised 711 cities, which formed the basis for all subsequent analyses.

**Variables** To quantify vegetation-mediated cooling under distinct hydroclimatic conditions, UGS types were grouped into four functional categories: i) sparse vegetation (bare and sparsely vegetated

areas), ii) open vegetation (grass and cropland), iii) woody type (trees and shrubs) and iv) hydric type (wetlands and mangroves). Cooling intensity was calculated as  $\Delta LST = LST_{UGS} - LST_{grey}$ , using LST derived from Landsat 8 (30 m resolution) via the Statistical Mono-Window (SMW) algorithm implemented in Google Earth Engine<sup>58</sup>. NDVI was derived from Landsat 8 surface reflectance data using the red and near-infrared bands<sup>59</sup>. LST values were averaged when more than two observations from the same acquisition date were available within an urban polygon.

To ensure seasonal comparability between hemispheres, months in the southern hemisphere were shifted by six months (e.g. December to June), such that month 1 corresponded to mid-winter and month 7 to mid-summer globally. Based on the monthly mean LST within each climate zone, July was identified to characterise the hottest conditions. LST and NDVI data were compiled for the period 2013–2023, but our main analyses focused on the most recent five-year period (2018–2022) to maximise data consistency across sensors and ancillary datasets and to reduce potential biases associated with urban expansion and sensor availability (see *Sensitivity and robustness*).

Precipitation regimes were classified using Köppen–Geiger subclasses into three categories reflecting water availability relative to evapotranspiration: i) dry (desert, steppe), ii) seasonally dry (savannah, dry summer, dry winter) and iii) wet (rainforest, monsoon, no dry season). This classification captures differences in the degree and seasonality of moisture limitation, reflecting variations in water availability most relevant to vegetation functioning and evaporative cooling. Throughout the manuscript, we use “hydroclimatic” to refer to water-energy limitation processes associated with these precipitation regimes, while retaining “climate zone” for broader thermal classifications. Canopy height (m) for each land cover type within each urban site was derived from the 2020 ETH Global Canopy Height Map<sup>60</sup>. Impervious surface cover (%) within each urban boundary was calculated as the proportion of pixels classified as built-up in the 2019 Copernicus Global Land Cover dataset. All remote sensing preprocessing was conducted in Google Earth Engine (Python API), and statistical analyses were performed in R.

**Modelling analysis** To enable comparison across climate zones with differing thermal variability,  $\Delta LST$  values were normalized within each climate zone by the corresponding 5<sup>th</sup>–95<sup>th</sup> percentile LST range and transformed using a signed logarithmic function to reduce the influence of extreme values:

$$norm\_ \Delta LST = sign(\Delta LST) \cdot \log(1 + |\Delta LST|) \quad (\text{Equation 1})$$

This normalization allows cross-climate comparison and was supported by approximately balanced sample sizes among the climate zones. To assess the relative influence of ecological, climatic, and structural controls on UGS cooling, we modelled  $norm\_ \Delta LST$  as a function of vegetation greenness (NDVI), UGS type, hydroclimatic regime, climate zone, canopy height, season and urban area size as explanatory variables. City identity (city ID) and spatial coordinates (latitude and longitude) were included as random effects. Impervious surface cover was additionally tested to evaluate robustness.

Linear mixed-effect models (LMMs) were fitted for  $norm\_ \Delta LST$  using a hierarchical model-building strategy, with NDVI included as the baseline predictor, followed by UGS type and climatic factors and then structural variables (canopy height, season and urban area size). Random effects were subsequently added to account for spatial clustering across urban sites. Model selection was guided by combined thresholds of  $\Delta AIC_{df} < -5$  and  $\Delta R^2_m > 0.01$ <sup>61</sup> to ensure that model improvements reflected substantive gains in explanatory power. Model uncertainty was quantified using 500 semiparametric bootstrap replicates to estimate 95% confidence intervals for marginal and conditional  $R^2$ .

To characterise nonlinear NDVI- $\Delta$ LST relationships, we further fitted generalized additive mixed models (GAMMs). NDVI smooths were stratified by UGS type, hydroclimatic regime and climate zone, with spatial random effects represented by smooth terms. Model performance was evaluated using penalized likelihood (fREML), adjusted  $R^2$ , deviance explained and smooth term significance. Concurvity diagnostics were used to assess redundancy among smooths, and backward selection was applied to achieve parsimonious and interpretable models. Weighted and unweighted fits were compared to evaluate the robustness and heteroscedasticity, and residual autocorrelation was examined using partial autocorrelation functions (PACF). Predictions from final GAMMs were generated with spatial coordinates fixed at their mean values to isolate ecological and hydroclimatic effects.

**NDVI transitions and cooling efficiency** To identify greenness-dependent cooling behaviour, two NDVI-based metrics were derived from the GAMM-predicted NDVI- $\Delta$ LST relationships. The cooling onset (NDVI-ZC) was defined as the NDVI value at which the predicted  $\Delta$ LST crossed zero, representing the transition from neutral or warming conditions to net surface cooling along a smooth nonlinear response. For each hydroclimatic regime, climate zone and UGS type, NDVI-ZC was estimated by linear interpolation across predicted NDVI sequences within the observed range. The lowest NDVI value at which a zero-crossing occurred was retained to represent the earliest onset of cooling. To characterise cooling under extreme heat, defined as the hottest 10% of observations based on background LST, we defined the cooling optimum (NDVI-opt) as the NDVI corresponding to the most negative predicted  $\Delta$ LST, indicating the maximum cooling efficiency. NDVI-opt was identified within the observed NDVI range of the hottest observations subset to avoid extrapolation. Cooling efficiency ( $^{\circ}\text{C}$  per unit NDVI) was calculated as the numerical first derivative of GAMM-predicted NDVI- $\Delta$ LST curves using finite differences, smoothed with a centred moving average filter. Cooling efficiency curves were derived separately for hydroclimatic regimes and UGS types using stratified model predictions.

**Sensitivity and robustness** We conducted targeted sensitivity and robustness analyses to assess the stability of NDVI- $\Delta$ LST relationships and derived transition metrics. Sensitivity analyses examined alternative temporal aggregation windows (1-year: 2019; 3-year: 2018–2020; 10-year: 2013–2023) relative to the 5-year baseline (2018–2022) (Supplementary Fig. S22) as well as alternative NDVI discretisation schemes (bin widths of 0.02 and 0.05; Supplementary Table S10). Robustness tests evaluated alternative representations of greenness by replacing Landsat-derived NDVI (30 m, 8-day) with MODIS NDVI (1 km, 16-day) while holding LST constant (Supplementary Table S11; Supplementary Fig. S23). We also recalculated NDVI using buffer radii of 3 km and 10 km around urban centroids (Supplementary Table S11). NDVI-ZC estimates shifted to lower values under larger buffer definitions relative to the main analysis, consistent with broader landscape-level vegetation context reducing local thermal contrast between green and grey surfaces. NDVI-ZC estimates were also similar, derived from models fitted to untransformed  $\Delta$ LST values (Supplementary Fig. S24), indicating that inferred cooling onset patterns were not driven by the response transformation.

### Data availability

Global urban boundaries with urban area sizes are available from Start Cloud Data Service Platform (<https://data-starcloud.pcl.ac.cn/iearthdata/14>). European Space Agency (ESA) World Cover 10 m 2021 product ([https://developers.google.com/earth-engine/datasets/catalog/ESA\\_WorldCover\\_v200](https://developers.google.com/earth-engine/datasets/catalog/ESA_WorldCover_v200)). Landsat 8 LST and NDVI data with 30 m resolution are available at [https://developers.google.com/earth-engine/datasets/catalog/LANDSAT\\_LC08\\_C02\\_T1\\_L2](https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2). Landsat LST calculation code is publicly available at [https://code.earthengine.google.com/?accept\\_repo=users/sofiaermida/landsat\\_smw\\_lst](https://code.earthengine.google.com/?accept_repo=users/sofiaermida/landsat_smw_lst). NDVI data

with 1 km resolution from MODIS (MOD13A2.061) product is available at [https://developers.google.com/earth-engine/datasets/catalog/MODIS\\_061\\_MOD13A2](https://developers.google.com/earth-engine/datasets/catalog/MODIS_061_MOD13A2). Canopy height data from ETH Global Canopy Height Map (2020) is available at <https://nlang.users.earthengine.app/view/global-canopy-height-2020>. Global climate zones and hydroclimate regimes are based on the Köppen-Geiger climate map (<https://koeppen-geiger.vu-wien.ac.at/present.htm>). The percentage of impervious surface data is calculated from Copernicus Global Land Cover Layers ([https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS\\_Landcover\\_100m\\_Proba-V-C3\\_Global](https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_Landcover_100m_Proba-V-C3_Global)).

### Code availability

Codes have been deposited in Figshare and are available to editors and reviewers during peer review via a private link (<https://figshare.com/s/0c842bc40b9b851e3e7e>). The repository will be made publicly accessible upon acceptance.

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