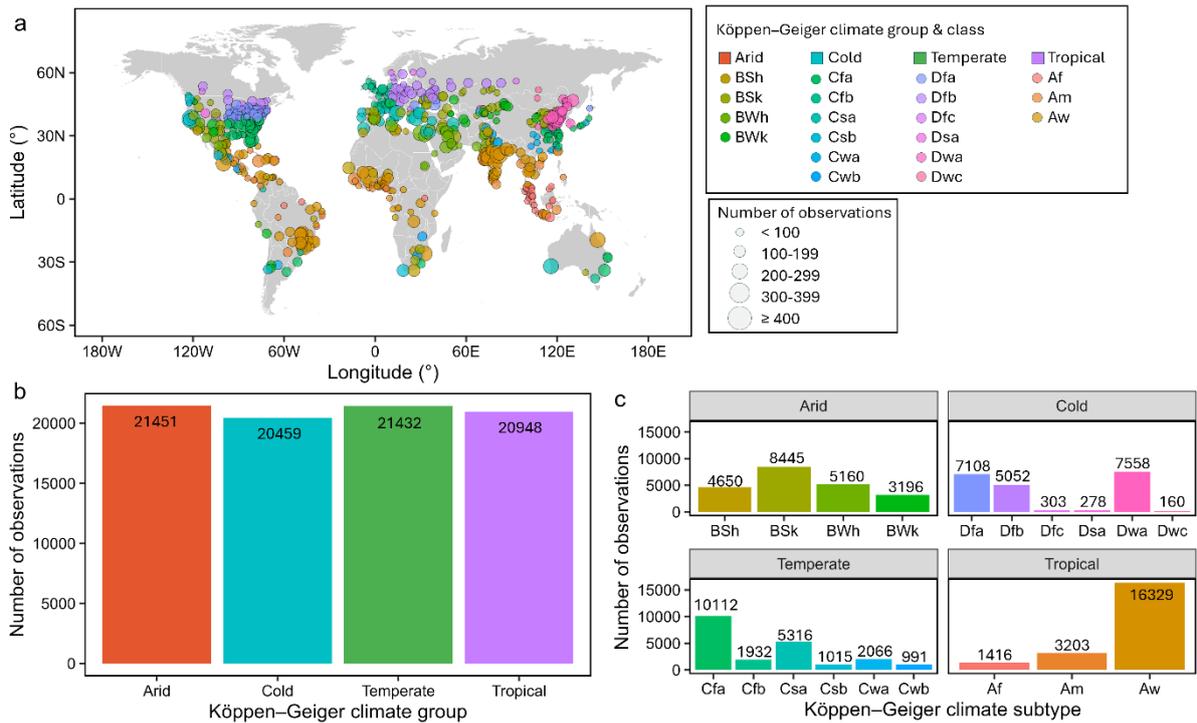**Supplementary Information for:**

**Global hydroclimatic constraints on greening transitions for urban cooling**

Supplementary Figure S1 | Global distribution of observations across Köppen-Geiger climate zones. a) Spatial distribution of cities coloured by Köppen–Geiger sub-climate class. Symbol sizes indicate the number of observations per city, grouped into sample-size bins (total observations = 84,422). **b)** Number of observations aggregated by major climate zones. Cities are approximately distributed in each climate zone (arid, n =176; cold, n = 180; temperate, n = 180; tropical, n = 177). **c)** Number of observations by Köppen–Geiger sub-climate class. The specific numbers of observations are included in panels b-c. All panels demonstrate broad and balanced sampling across hydroclimatic regimes, supporting the robustness of global greening transition estimates.

Supplementary Table S1 | Selected global cities. The table lists the city name, country, continent, latitude, longitude, climate zone, precipitation regime, median NDVI, and median ΔLST (difference in land surface temperature between urban green and grey spaces; °C) for 711 cities worldwide over the 5 years from 2018 to 2022. The full dataset is provided in a separate Excel spreadsheet.
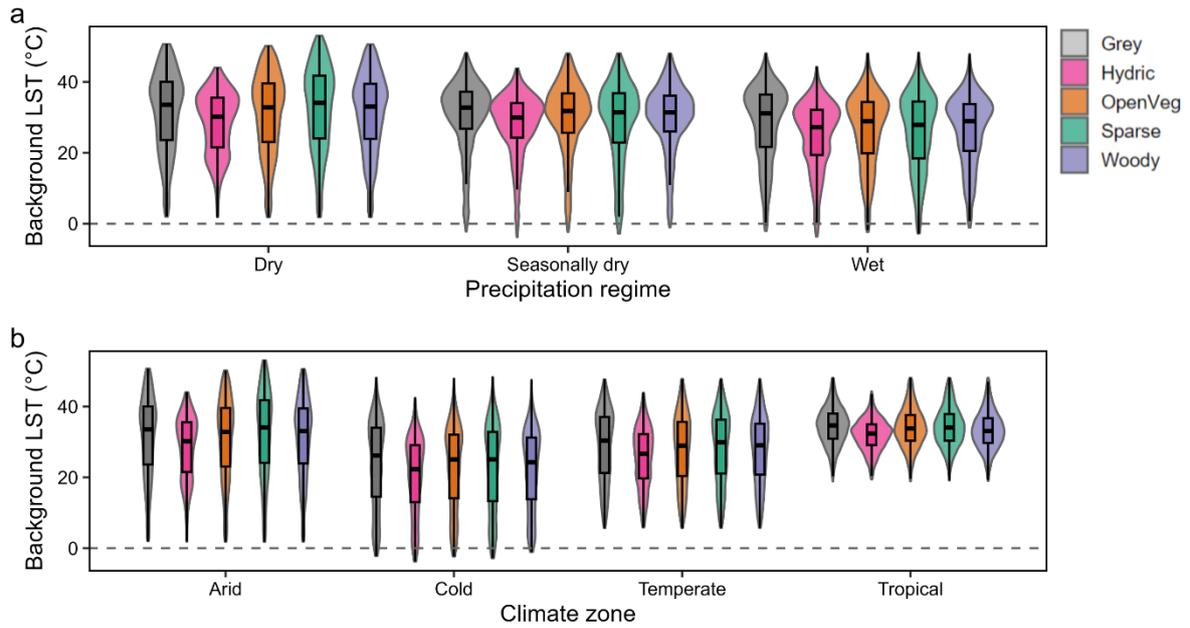
Supplementary Figure S2 | Background LST distributions across precipitation regimes and climate zones.
Violin plots embedded with boxplots show background land surface temperature (LST; °C) distributions by surface type (grey and urban green spaces) across **a)** precipitation regimes (dry, seasonally dry and wet) and **b)** climate zones (arid, cold, temperate and tropical). Boxplots within violin plots indicate medians and interquartile ranges, and the horizontal dashed line marks background LST = 0 °C. Background LST values were restricted to the 1st – 99th percentiles within each surface group to reduce the influence of extreme outliers in visualisation.
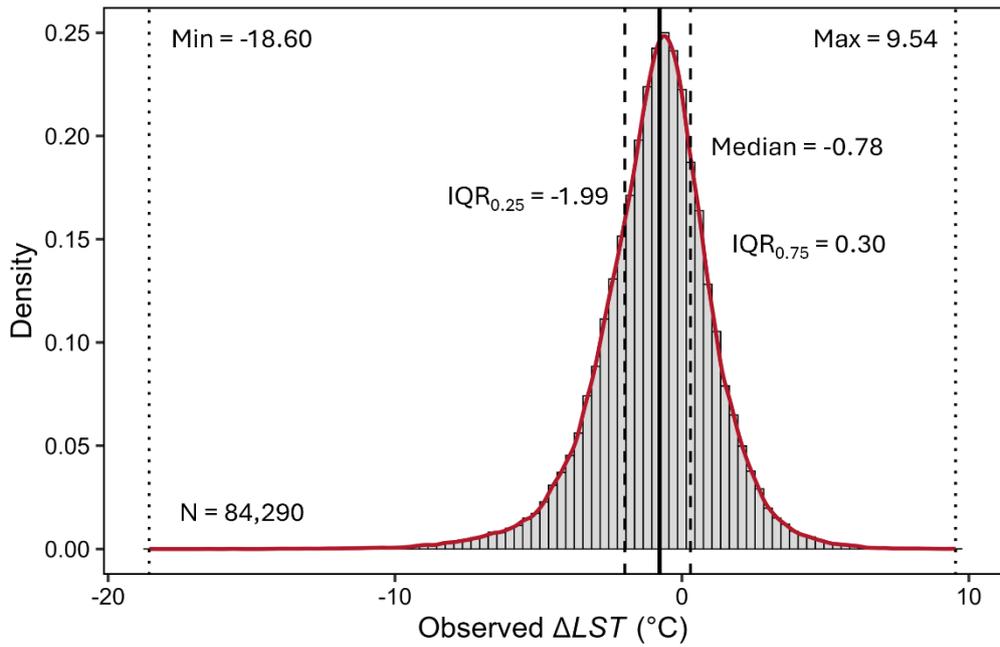
**Supplementary Figure S3 | Density distribution of observed ΔLST.** Histogram and kernel density estimate of observed ΔLST (difference in land surface temperature between urban green and grey spaces; °C) for matched observations by date (n = 84,290). Solid, dashed, and dotted vertical lines indicate the median, interquartile range (IQR; 25th–75th percentiles), and full range (minimum–maximum), respectively.

Supplementary Table S2 | Summary of observed ΔLST across UGS, precipitation, climate and latitude groups. The number of observations (n) and the median observed ΔLST (difference in land surface temperature between urban green and grey spaces; °C) with interquartile range (IQR; 25th – 75th percentiles) across urban green space (UGS) type (sparse vegetation, open vegetation, hydric and woody), precipitation regime (dry, seasonally dry and wet), Köppen–Geiger climate zone (arid, cold, temperate and tropical) and latitudinal (30-60 °S, 0-30 °S, 0-30 °N, 30-60 °N and 60-90 °N) bins. Total values represent the sum of observations and the median of subgroup medians, IQR at 25th and 75th percentiles across all subsets.

	N	Median	$IQR_{0.25}$	$IQR_{0.75}$	Min	Max
UGS group						
Hydric	6,752	-3.10	-5.00	-1.55	-18.57	8.70
OpenVeg	36,814	-0.41	-1.56	0.61	-11.33	9.54
Sparse	15,906	-0.19	-1.15	0.85	-13.85	8.54
Woody	24,818	-1.25	-2.32	-0.38	-15.57	7.80
Total	84,290	-0.83	-1.94	0.11	-14.71	8.62
Precipitation group						
Dry	21,451	0.02	-1.12	1.13	-15.57	8.54
Seasonally dry	33,713	-0.54	-1.62	0.43	-16.51	9.54
Wet	29,126	-1.56	-2.75	-0.62	-18.57	9.48
Total	84,290	-0.54	-1.62	0.43	-16.51	9.48
Climate group						
Arid	21,451	0.02	-0.05	-1.12	1.13	-15.57
Cold	20,459	-1.08	-1.33	-2.34	-0.09	-15.69
Temperate	21,432	-1.08	-1.30	-2.34	-0.12	-18.57
Tropical	20,948	-0.90	-0.94	-1.98	0.16	-11.64
Total	84,290	-0.99	-1.12	-2.16	0.03	-15.63
Latitude group						
30-60 °S	2,164	-0.13	-1.25	1.19	-13.75	8.54
0-30 °S	7,962	-0.97	-2.02	0.03	-13.53	8.71
0-30 °N	23,654	-0.71	-1.83	0.45	-14.20	9.54
30-60 °N	50,433	-0.80	-2.08	0.24	-18.57	9.48
60-90 °N	77	-1.57	-2.47	-0.34	-5.85	3.06
Total	84,290	-0.80	-2.02	0.24	-13.75	8.71
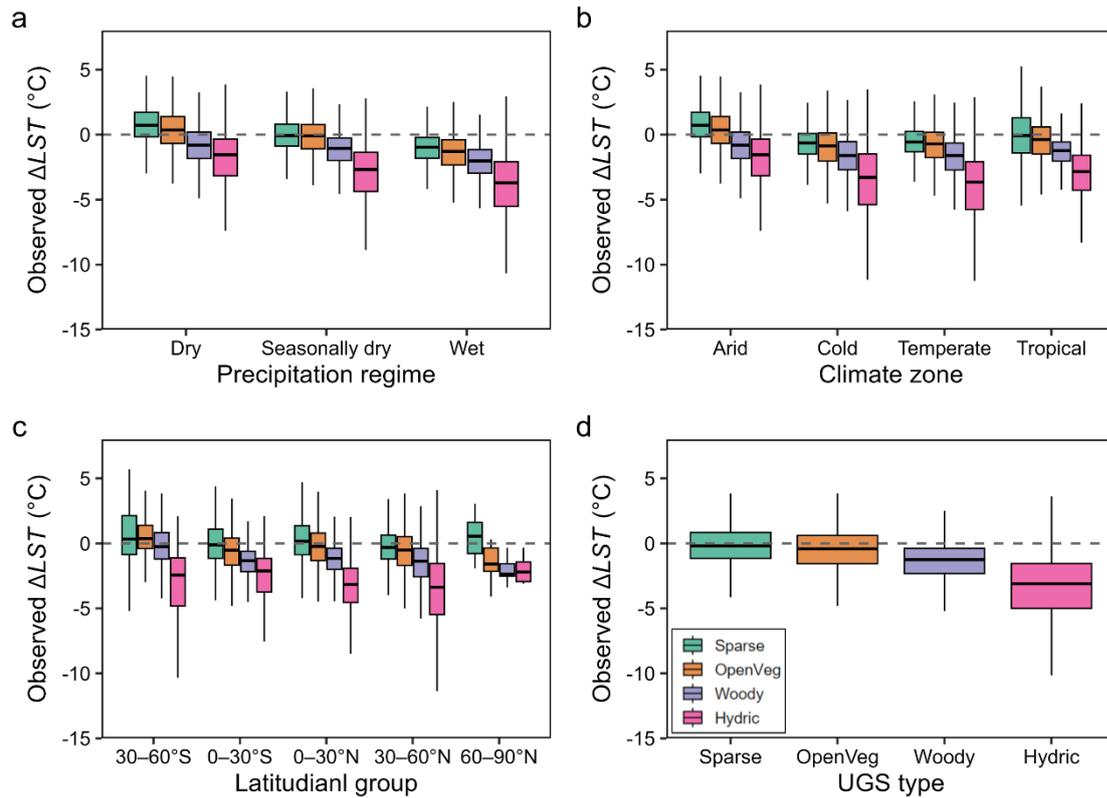
Supplementary Figure S4 | Observed ΔLST across precipitation, climate, latitudinal and UGS groups. Boxplots show observed ΔLST (difference in land surface temperature between urban green and grey spaces; °C) by **a)** precipitation regime (dry, seasonally dry and wet), **b)** climate zone (arid, cold, temperate and tropical), **c)** latitudinal group (30-60 °S, 0-30 °S, 0-30 °N, 30-60 °N and 60-90 °N) and **d)** urban green space (UGS) type (sparse vegetation, open vegetation, woody and hydric). Panels a-c are stratified by UGS type. In all panels, boxes represent the interquartile range with median values indicated, and the horizontal dashed line marks observed ΔLST = 0 °C.
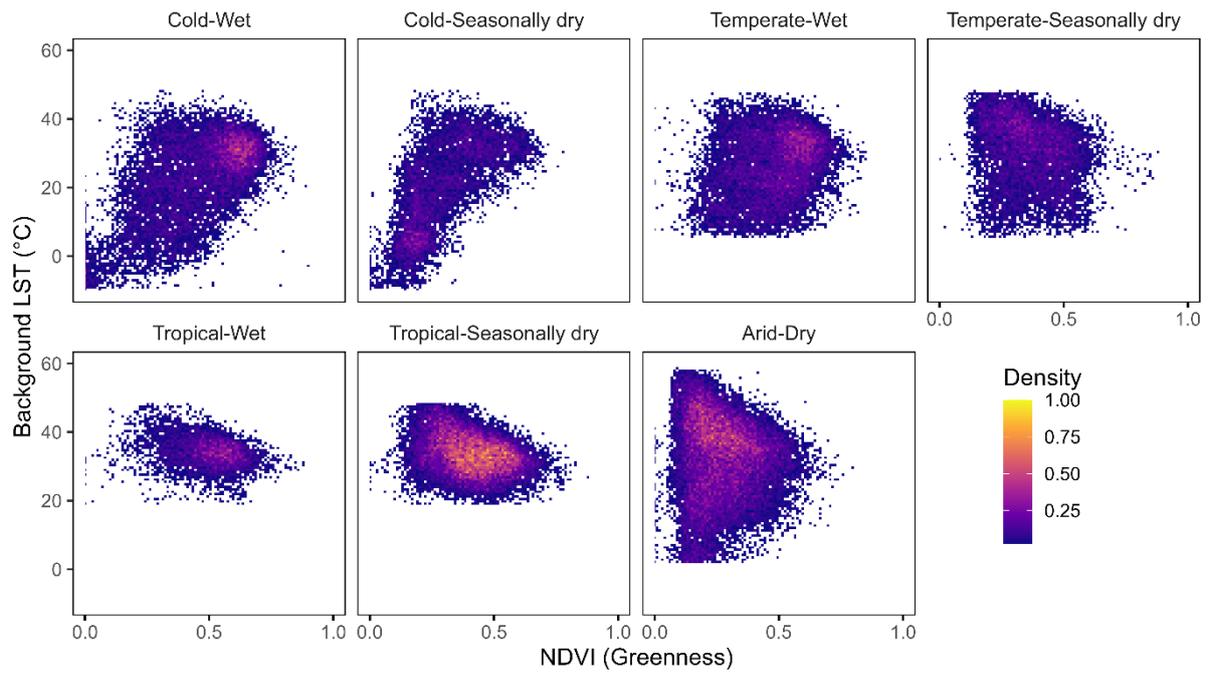
Supplementary Figure S5 | Heatmaps of NDVI and background LST across hydroclimatic groups. Two-dimensional density distributions illustrate the relationship between vegetation greenness (NDVI) and background land surface temperature (LST; °C) within each hydroclimatic group (n = 84,290). Colour intensity indicates the relative density of observations within each group.

Supplementary Table S3 | Linear mixed-effects models (LMMs) fitted to normalized ΔLST. The models were fitted to normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C) observations (n = 84,290). Explanatory variables (NDVI, UGS type, precipitation regime, climate zone, canopy height, season and urban area size) and random effects (latitude [n = 709], longitude [n = 710] and city ID [n=711]) were added hierarchically. Model fit was evaluated using marginal and conditional R^2 (R^2_m and R^2_c), changes in AIC (ΔAIC_{df}) and changes in marginal R^2 (ΔR^2_m) and conditional R^2 (ΔR^2_c). Parsimony criteria were set as follows: $\Delta AIC_{df} < -5$ and $\Delta R^2_m > 0.01$ for fixed effects; $\Delta AIC_{df} < -5$ and $\Delta R^2_c > 0.01$ for random effects. Model M4 was initially selected as a final LMM based on the selection criteria. Although longitude did not independently meet the selection thresholds, it was retained as an additional random effect to account for residual spatial structure and improve model stability in subsequent GAMM analyses. The final LMM thus is model M4_R1 and its result is shown in Supplementary Table S4.

| Model	Fixed effects	Random effects	df	R^2_m	R^2_c	ΔAIC_{df}	ΔR^2_{mdf}/ ΔR^2_{cdf}
Full model: normalized ΔLST ~ NDVI + UGS + Precipitation regime + Climate zone + Canopy height + Season + Urban area size + (1 | latitude) + (1 | longitude) + (1 | city id)							
Null	1 + (1|Latitude)		3	0.000	0.303	0	0.000
M1	Null + NDVI		4	0.236	0.409	-18,539	0.236
M2	M1 + UGS type		7	0.330	0.486	-11,948	0.095
M3	M2 + Precipitation regime		9	0.368	0.507	-45	0.037
M4	M3 + Climate zone		11	0.390	0.512	-66	0.019
M5	M4 + Canopy height		12	0.390	0.513	-89	0.004
M6	M4 + Season		14	0.390	0.516	-633	0.003
M7	M4 + Urban area size		12	0.390	0.515	-17	0.003
M4_R1	M4	+ Longitude	12	0.382	0.514	-78	0.002
M4_R2	M4	+ City ID	12	0.383	0.513	-92	0.001
M4_R3	M4_R1	+ City ID	13	0.383	0.513	-12	-0.001

Supplementary Table S4 | Final linear mixed-effects model (LMM) fitted to normalized ΔLST. The model includes NDVI, UGS type, precipitation regime and climate zone as fixed effects (n = 84,290). Latitude (n = 709) and longitude (n = 710) were set as random effects. The final model result is presented with bootstrapped 95% confidence intervals based on 500 semiparametric replicates.

Final model: normalized ΔLST ~ NDVI + UGS + Precipitation regime + Climate zone + (1 | latitude) + (1 | longitude)

Random effects	Variance	Std. Dev.	Fixed effects	Estimate ±SE	T value
Latitude (°)	5.09×10^{-4}	0.023	(Intercept)	$-0.008 \pm 2.39 \times 10^{-3}$	-3.26
Longitude (°)	3.10×10^{-4}	0.018	NDVI	$-0.225 \pm 1.76 \times 10^{-3}$	-127.94
			UGS – Open vege	$0.085 \pm 0.80 \times 10^{-4}$	106.76
			UGS – Sparse	$0.066 \pm 0.90 \times 10^{-4}$	72.50
			UGS – Woody	$0.056 \pm 0.82 \times 10^{-4}$	68.15
			Precip – Seasonally dry	$-0.022 \pm 3.30 \times 10^{-3}$	-6.73
			Precip – Wet	$-0.039 \pm 3.59 \times 10^{-3}$	-10.85
			Climate – Cold	$0.022 \pm 3.22 \times 10^{-3}$	6.98
			Climate – Temperate	$0.025 \pm 3.23 \times 10^{-3}$	7.78

AIC = -245,449; df = 12; R^2_m = 0.386; R^2_c = 0.512; n = 84,290;

Bootstrapped R^2_m = 0.358 (95% CI: 0.337 – 0.383); R^2_c = 0.493 (95% CI: 0.471 – 0.515)
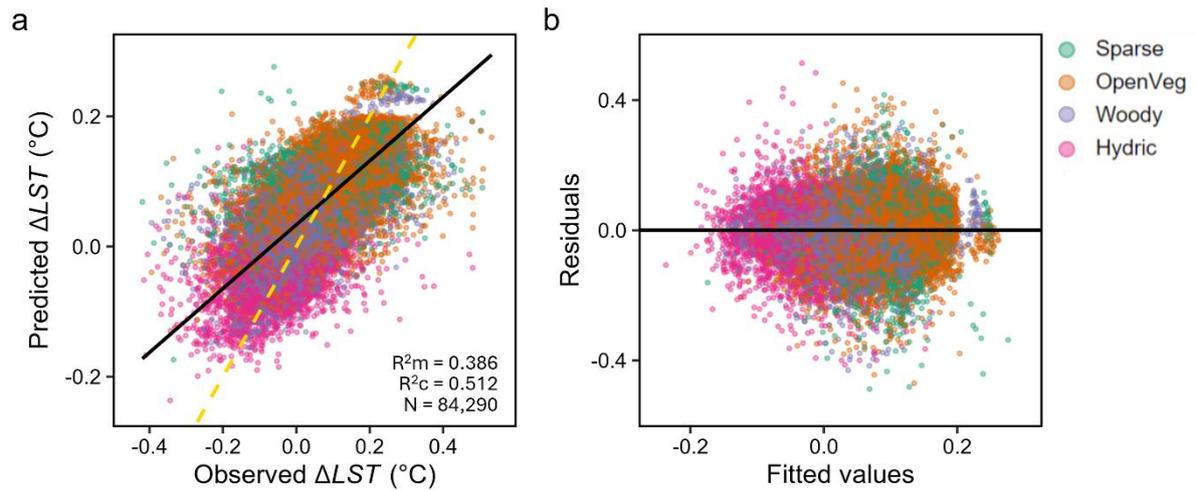
Supplementary Figure S6 | Model diagnostics of the final linear mixed-effects model (LMM). a) Predicted versus observed ΔLST (difference in land surface temperature between urban green and grey spaces; °C), incorporating fixed (UGS type, precipitation regime and climate zone) and random effects (latitude and longitude) across UGS type. The solid black line indicates the fitted linear regression across all fixed effects, including UGS, precipitation and climate groups, and the dashed yellow line represents the 1:1 reference. **b)** Residuals of the final LMM with the horizontal solid black line at y = 0, indicating the baseline of zero residual error.

Supplementary Table S5 | Final generalised additive mixed model (GAMM). Final GAMM was fitted to normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C) observations (n = 84,290) with *'discrete = FALSE'* to allow for accurate variance estimation and to account for heteroscedasticity in model residuals. Urban green space (UGS) type, precipitation regime and climate zone were included as fixed effects and smooth terms for NDVI stratified by the interactions across all three variables. Latitude (n = 709) and longitude (n = 710) were included as smooth random effects. Reported edfs correspond to the estimated degrees of freedom for each smooth term. All parametric terms and smooth terms were significant ($p < 2.0 \times 10^{-16}$ ***).

Significant codes: $p < 0.001$ ***, $p < 0.001$ ** and $p < 0.01$ *.

Formula: norm_ΔLST ~ UGS + precip + climate + s(NDVI, by = interaction(UGS, precip, climate), k = 6) + s(lat, lng, bs = "re")

GAMMs	R^2_{adj}	fREML	Scale Est.	Concurvity	Smooth *p*-value	Parametric *p*-value
Full model	0.440	-1.19×10^5	3.41×10^{-3}	All < 0.72	All ***	All ***

Term	Estimate ± SE	T value	s(NDVI) by UGS × precip × climate	edf (min – max)	F (min – max)
(Intercept)	$-0.10 \pm 1.22 \times 10^{-3}$	-82.94	s(NDVI) by UGS × precip × climate	3.24-4.98	23.32-1192.82
UGS – Open vege	$0.09 \pm 1.12 \times 10^{-3}$	77.5	s(lat, lng)	1	335.38
UGS – Sparse	$0.07 \pm 1.38 \times 10^{-3}$	50.38			
UGS – Woody	$0.06 \pm 1.22 \times 10^{-3}$	52.26			
Precip – Seasonally Dry	$-0.02 \pm 1.09 \times 10^{-3}$	-14.81			
Precip – Wet	$-0.02 \pm 1.38 \times 10^{-3}$	-15.73			
Climate – Cold	$0.01 \pm 1.04 \times 10^{-3}$	12.11			
Climate - Temperate	$0.02 \pm 1.22 \times 10^{-3}$	14.52			
Climate - Tropical	0	NaN			

Supplementary Table S6 | Final generalised additive mixed model (GAMM) with *'discrete = TRUE'.* Final GAMM was fitted to normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C) observations (n = 84,290) with *'discrete = TRUE'* to ensure reproducible smooth estimates for comparison with supplementary Table S5 (discrete = FALSE). Urban green spaces (UGS) type, precipitation regime and climate zone were included as fixed effects and smooth terms for NDVI stratified by the interactions across all three variables. Latitude (n = 709) and longitude (n = 710) were included as smooth random effects. Reported edfs correspond to the estimated degrees of freedom for each smooth term. All non-reference parametric and smooth terms were significant ($p < 2.0 \times 10^{-16}$***), unless otherwise noted.

Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s., not significant.

Formula: norm_ΔLST ~ UGS + precip + climate + s(NDVI, by = interaction(UGS, precip, climate), k = 6) + s(lat, lng, bs = "re")

GAMMs	R^2_{adj}	fREML	Scale Est.	Concurvity	Smooth p-value	Parametric p-value
Full model with discrete = TRUE	0.449	-1.12 ×10^5	3.35×10^{-3}	All < 0.99	All ***	Temperate ($p < 0.03$*), precip-wet (n.s.) cold climate (n.s.)

| Term	Estimate ± SE	T value	s(NDVI) by UGS × precip × climate	edf (min – max)	F (min – max)
(Intercept)	-0.11 ± 3.66 ×10^{-3}	-29.80	s(NDVI) by UGS × precip × climate	1.00-4.94	27.55-1,277.88
UGS – Open vege	0.06 ± 2.52×10^{-3}	22.08	s(lat, lng)	1	521.21
UGS – Sparse	0.05 ± 3.87 ×10^{-3}	12.01			
UGS – Woody	0.07 ± 3.18 ×10^{-3}	21.83			
Precip – Seasonally Dry	0	NaN			
Precip – Wet	0.0001 ± 3.30 ×10^{-3}	-0.02			
Climate – Cold	0.002 ± 4.76 ×10^{-3}	0.49			
Climate - Temperate	0.01 ± 5.29 ×10^{-3}	2.13			
Climate - Tropical	-0.09 ± 6.22 ×10^{-3}	-14.60			

Supplementary Table S7 | Diagnostics of backward-selection for final generalised additive mixed models (GAMMs). Backward-selection for final GAMMs was fitted to normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C) observations (n = 84,290) with *'discrete = FALSE'* to verify the stability of the full model. Latitude (n = 709) and longitude (n = 710) were included as smooth random effects. Urban green space (UGS) type, precipitation regime and climate zone were included as fixed effects and smooth terms for NDVI stratified by the interactions across all three variables. Latitude (n = 709) and longitude (n = 710) were included as smooth random effects. Reported edfs correspond to the estimated degrees of freedom for each smooth term. All parametric terms and smooth terms were significant ($p < 2.0 \times 10^{-16}$***), unless otherwise noted.

Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s., not significant.

| GAMMs	R^2_{adj}	fREML	Scale Est.	Concurvity	Smooth *p*-value	Parametric *p*-value
Final selected model						
Full model norm_ΔLST ~ UGS + precip + climate + s(NDVI, by = interaction(UGS, precip, climate), k = 6)	0.440	-1.19×10^5	3.41×10^{-3}	All < 0.72	All ***	All ***
Backward selected model						
No UGS norm_ΔLST ~ precip + climate + s(NDVI, by = interaction(precip, climate), k = 6)	0.342	-1.13×10^5	4.00×10^{-3}	All < 0.46	All ***	All ***
No precip norm_ΔLST ~ UGS + climate + s(NDVI, by = interaction(UGS, climate, k = 6)	0.427	-1.19×10^5	3.48×10^{-3}	All < 0.69	All ***	All ***
No climate norm_ΔLST ~ UGS + precip + s(NDVI, by = interaction(UGS, precip, k = 6)	0.411	-1.18×10^5	3.58×10^{-3}	All < 0.68	All ***	All ***
UGS only norm_ΔLST ~ UGS + s(NDVI, by = UGS, k = 6)	0.391	-1.16×10^5	3.70×10^{-3}	All < 0.72	All ***	All ***
Precip only norm_ΔLST ~ precip + s(NDVI, by = precip, k = 6)	0.320	-1.12×10^5	4.13×10^{-3}	All < 0.62	All ***	All ***
Climate only norm_ΔLST ~ climate + s(NDVI, by = climate, k = 6)	0.332	-1.12×10^5	4.06×10^{-3}	All < 0.63	All ***	All ***

Supplementary Table S8 | Variance-weighted generalised additive mixed model (GAMM) for the final model. Variance-weighted GAMM for the final model was fitted to normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C) observations (n = 84,290) with 'discrete = FALSE' to account for heteroscedasticity in model residuals. Latitude (n = 709) and longitude (n = 710) were included as smooth random effects. Urban green space (UGS) type, precipitation regime and climate zone were included as fixed effects and smooth terms for NDVI stratified by the interactions across all three variables. Latitude (n = 709) and longitude (n = 710) were included as smooth random effects. Reported edfs correspond to the estimated degrees of freedom for each smooth term. All parametric terms and smooth terms were significant ($p < 2.0 \times 10^{-16}$***), unless otherwise noted.

Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s., not significant.

Formula: norm_ΔLST ~ UGS + precip + climate + s(NDVI, by = interaction(UGS, precip, climate), k = 6) + s(lat, lng, bs = "re")

GAMMs	R^2_{adj}	fREML	Scale Est.	Concurvity	Smooth p-value	Parametric p-value
Variance-weighted model	0.382	-1.20×10^5	1.000	All < 0.72	All ***	Temperate ($p < 0.032$ *)

| Term	Estimate ± SE	T value	s(NDVI) by UGS × precip × climate	edf (min − max)	F (min − max)
(Intercept)	$-0.10 \pm 1.30 \times 10^{-3}$	-78.95	s(NDVI) by UGS × precip × climate	3.39-4.97	9.16-999.28
UGS – Open vege	$0.09 \pm 1.20 \times 10^{-3}$	71.70	s(lat, lng)	0.997	302.78
UGS – Sparse	$0.07 \pm 1.42 \times 10^{-3}$	47.44			
UGS – Woody	$0.06 \pm 1.28 \times 10^{-3}$	50.39			
Precip – Seasonally Dry	$0.005 \pm 0.92 \times 10^{-3}$	5.05			
Precip – Wet	0	NaN			
Climate – Cold	$-0.01 \pm 0.95 \times 10^{-3}$	-8.54			
Climate - Temperate	$-0.003 \pm 1.32 \times 10^{-3}$	-2.17			
Climate - Tropical	$-0.02 \pm 1.37 \times 10^{-3}$	-14.12			
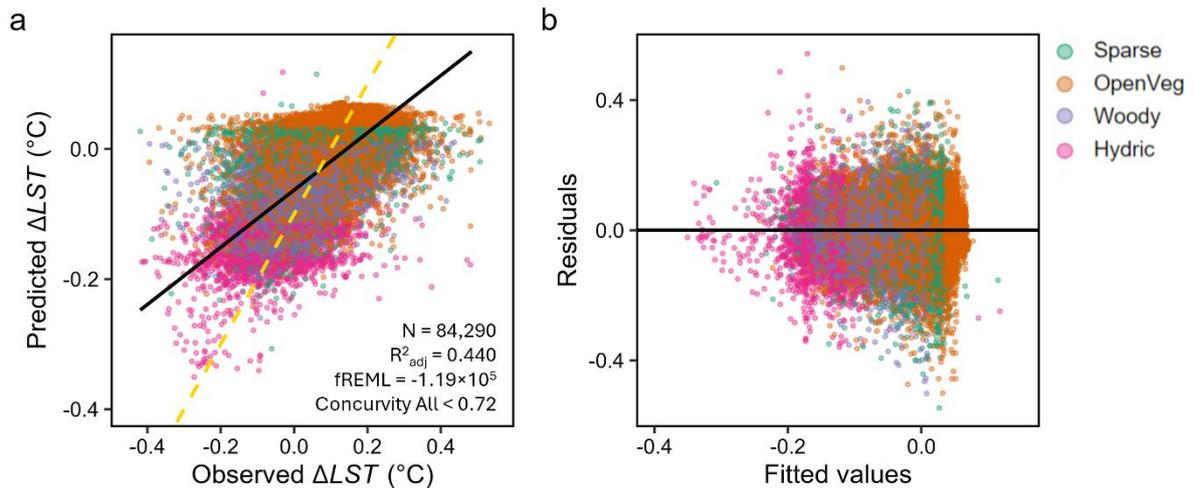
Supplementary Figure S7 | Diagnostics of the final generalised additive mixed model (GAMM). a) Observed versus GAMM-predicted normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types. The solid black line represents the fitted linear regression, and the dashed yellow line denotes the 1:1 reference. **b)** Residuals of the final GAMM, with the horizontal black line at y = 0 indicating zero residual error. Full model outputs are provided in Supplementary Table S5.
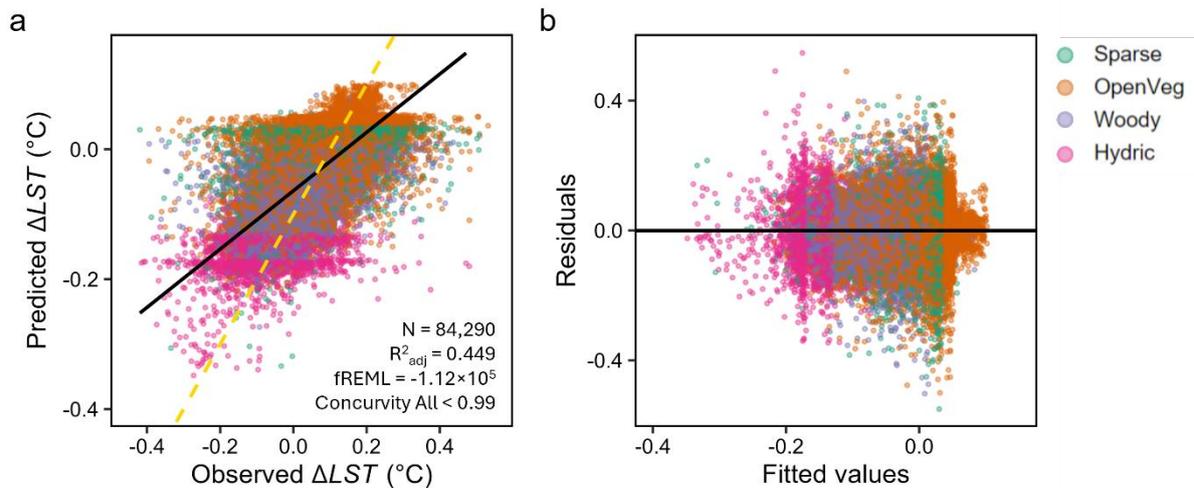
Supplementary Figure S8 | Diagnostics of the final generalised additive mixed model (GAMM) with '*discrete = TRUE'*. a) Observed versus GAMM-predicted normalised ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types. The solid black line represents the fitted linear regression, and the dashed yellow line denotes the 1:1 reference. **b)** Residuals of the final GAMM, with the horizontal black line at y = 0 indicating zero residual error. Full model outputs are provided in Supplementary Table S6.
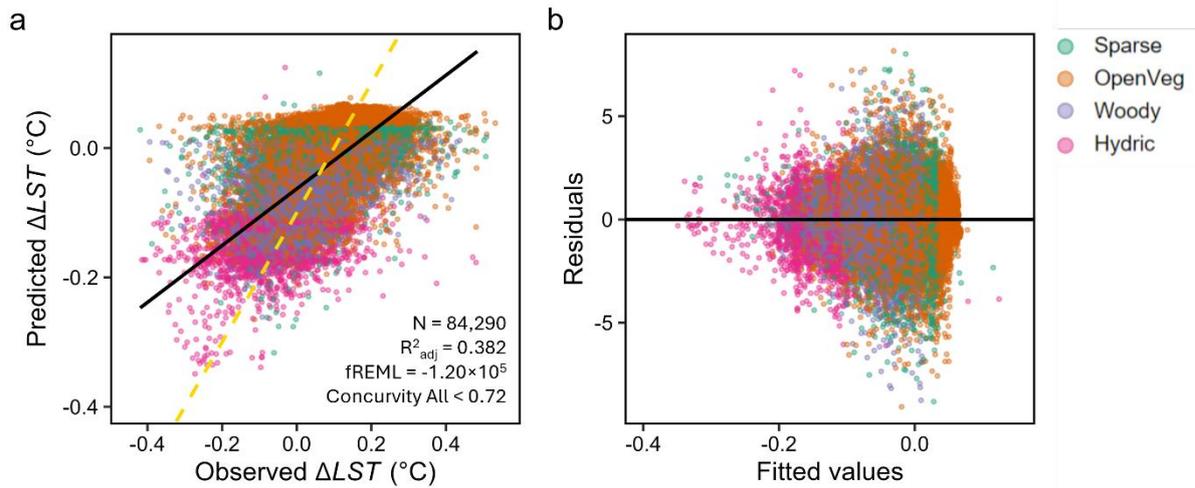
Supplementary Figure S9 | Diagnostics of the final variance-weighted generalised additive mixed model (GAMM) accounting for heteroscedasticity. a) Observed versus GAMM-predicted normalised ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types. The solid black line shows the fitted linear regression, and the dashed yellow line denotes the 1:1 reference. **b)** Residuals of the final GAMM, with the horizontal black line at y = 0 indicating zero residual error. Full model outputs are provided in Supplementary Table S8.
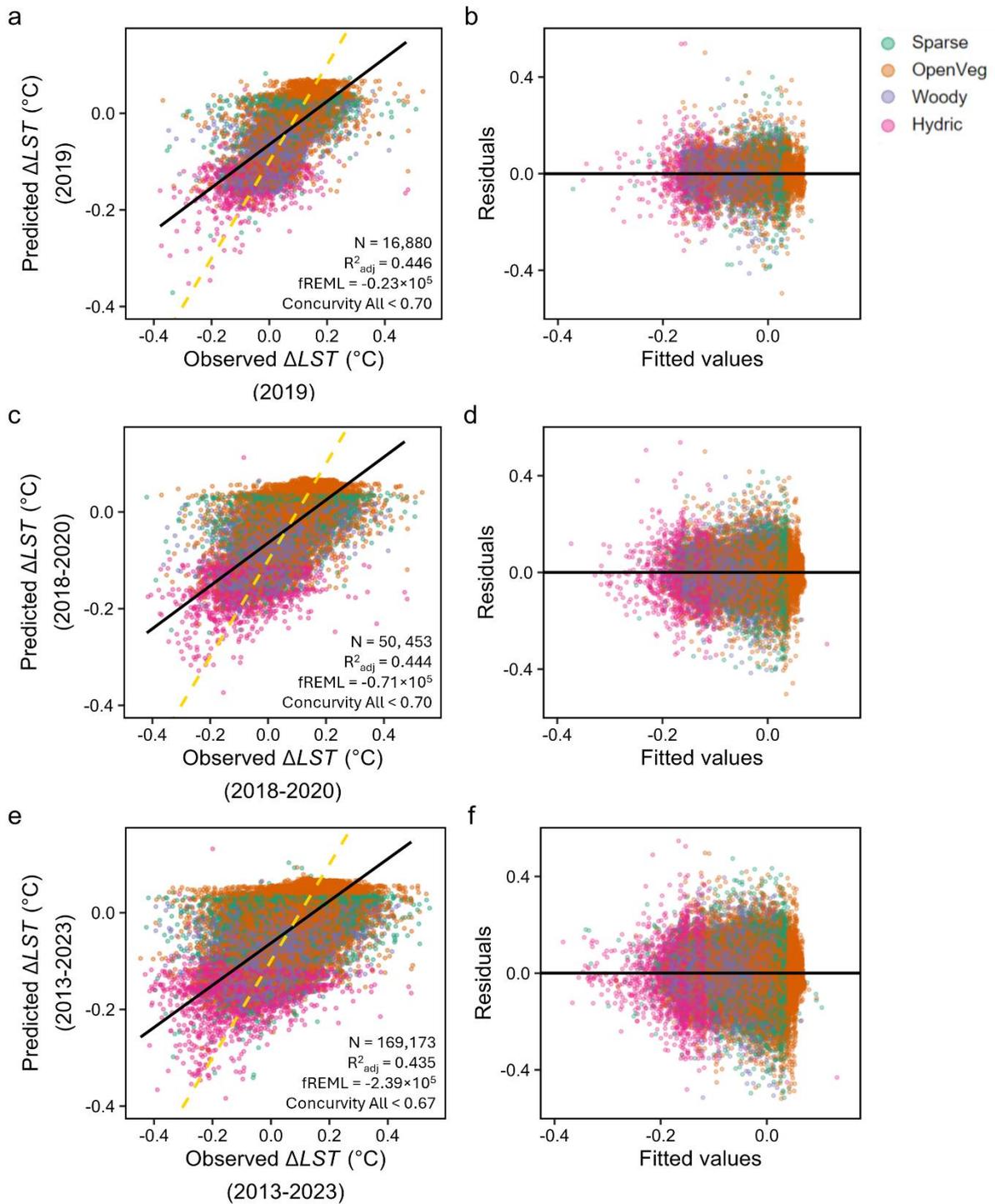
Supplementary Figure S10 | Diagnostics of model comparison between the temporal windows (1-, 3-, 10-years subsets). Observed versus GAMM-predicted normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types for **a-b)** 1 year (2019), **c-d)** 3 years (2018-2020) and **e-f)** 10 years (2013-2023). In panels a, c and e, the solid black lines show the fitted linear regression, and the dashed yellow lines denote the 1:1 reference. Panels b, d and f show residuals of the final GAMM, with the horizontal black lines at y = 0 indicating zero residual error.
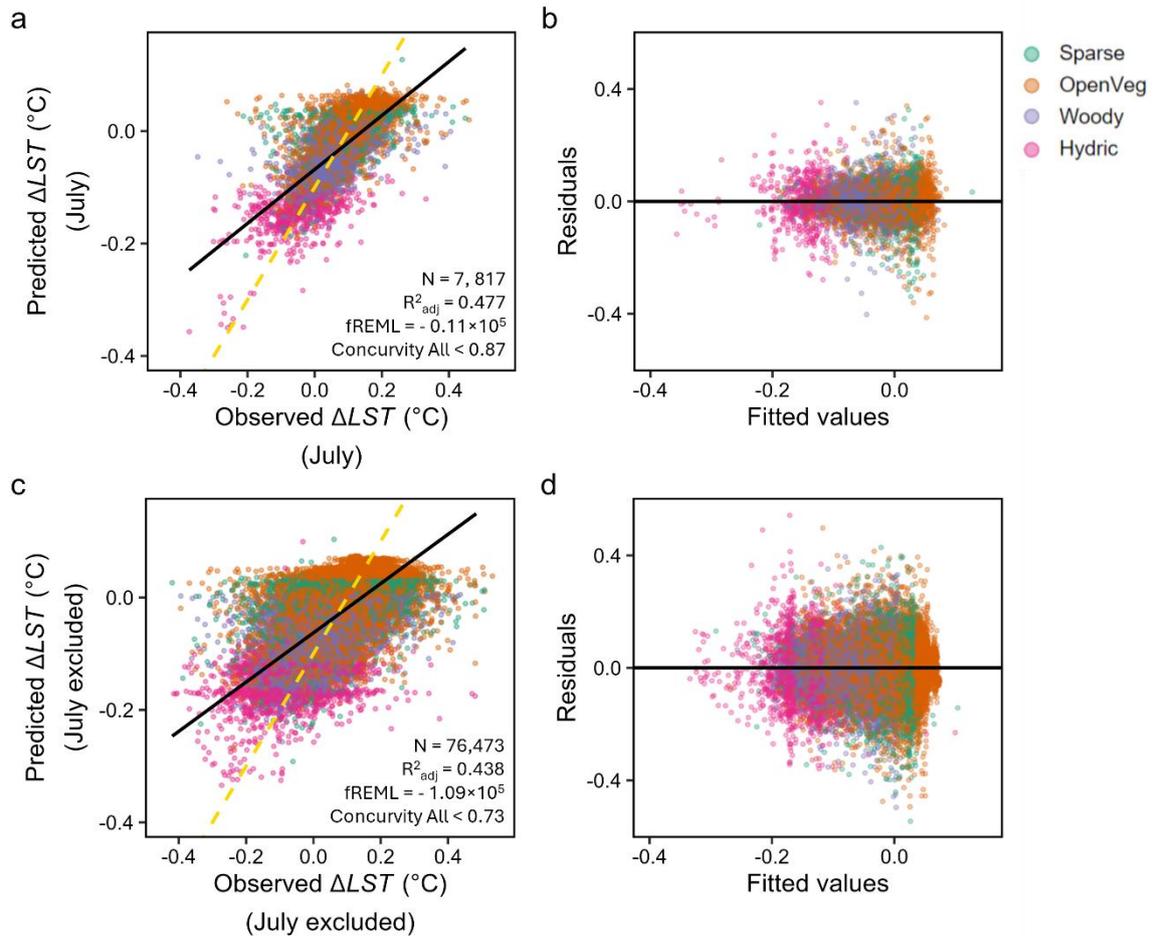
Supplementary Figure S11 | Diagnostics of model comparison between the hottest month (July) and the remaining months (July excluded). Observed versus GAMM-predicted normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types for **a-b)** the hottest month (July) and **c-d)** the remaining months (July excluded). In panels a and c, the solid black lines show the fitted linear regression, and the dashed yellow lines denote the 1:1 reference. Panels b and d show residuals of the final GAMM, with the horizontal black lines at y = 0 indicating zero residual error.
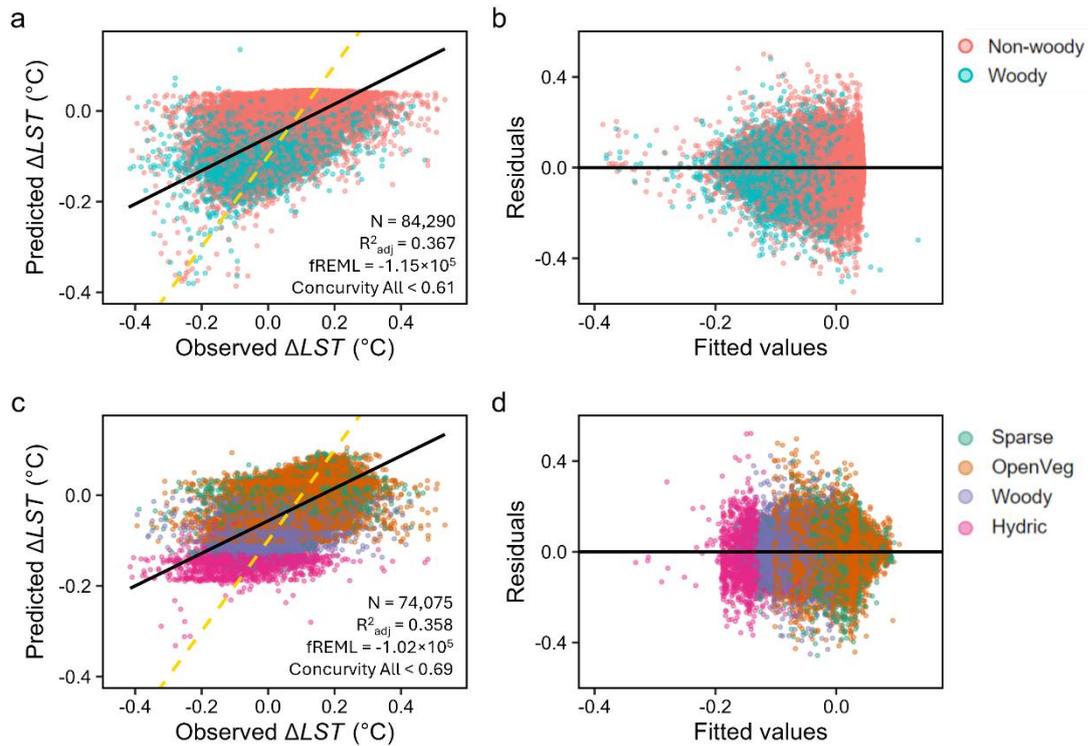
Supplementary Figure S12 | Robustness of GAMM results to alternative UGS specifications and spatial resolutions (MODIS, 1 km). Observed versus GAMM-predicted normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types. Panel **a-b)** shows model diagnostics after collapsing UGS into broad structural classes (non-woody: grass, crop, sparse and wetland versus woody: tree, shrub and mangroves). Panel **c-d)** shows corresponding diagnostics using NDVI derived from the MODIS product (1 km spatial resolution, 16-day composites). For panels a and c, the solid black lines show the fitted linear regression, and the dashed yellow lines denote the 1:1 reference. Panels b and d show residuals of the final GAMM, with the horizontal black lines at y = 0 indicating zero residual error.
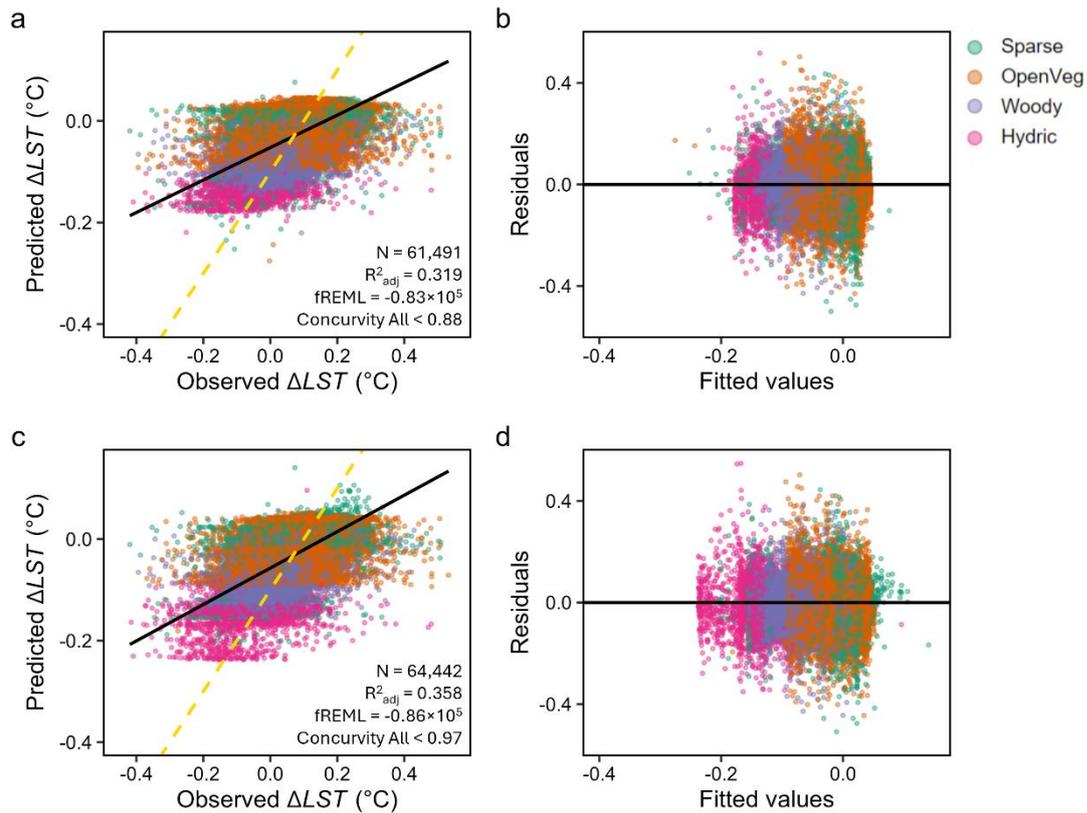
Supplementary Figure S13 | Robustness of GAMM results across alternative spatial scales of buffered NDVI greenness. Observed versus GAMM-predicted normalized ΔLST (difference in land surface temperature between urban green and grey spaces; °C), based on combined fixed effects and random smooths across urban green space (UGS) types. Buffer-averaged NDVI values were calculated within **a-b)** 3 km and **c-d)** 10 km radii around the centroids of urban polygons used in the main analysis. For panels a and c, the solid black lines indicate the fitted linear regression, and the dashed yellow lines denote the 1:1 reference. Panels b and d show residuals of the final GAMM, with the horizontal black lines at y = 0 indicating zero residual error.
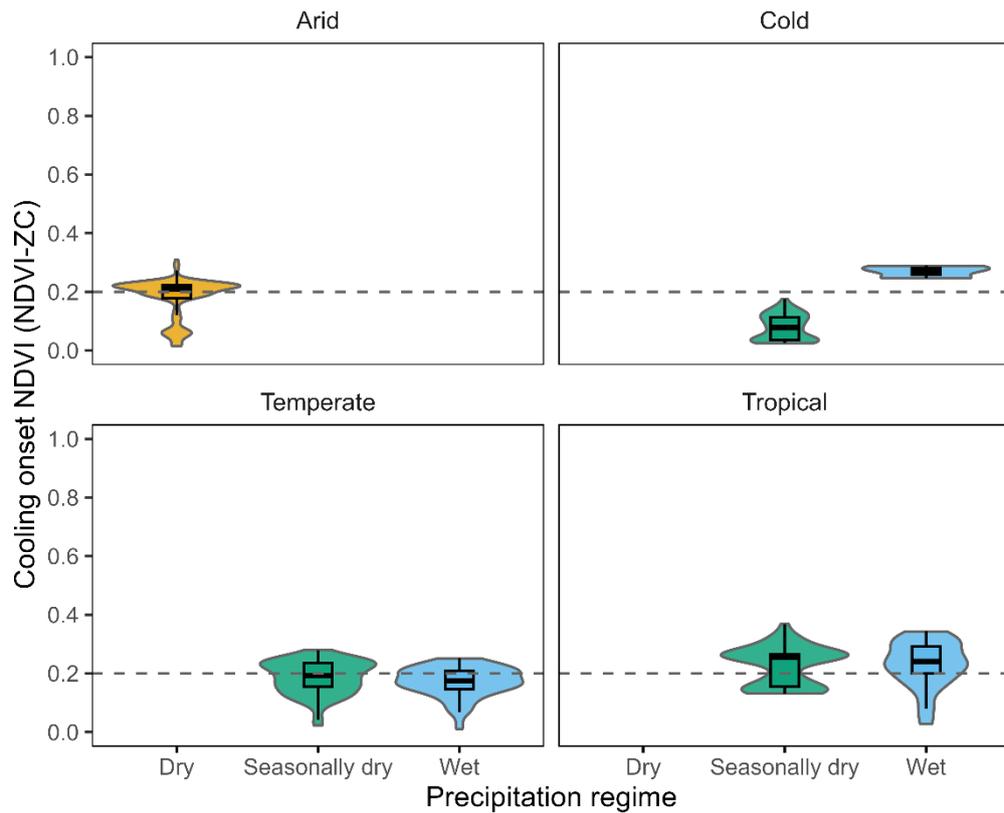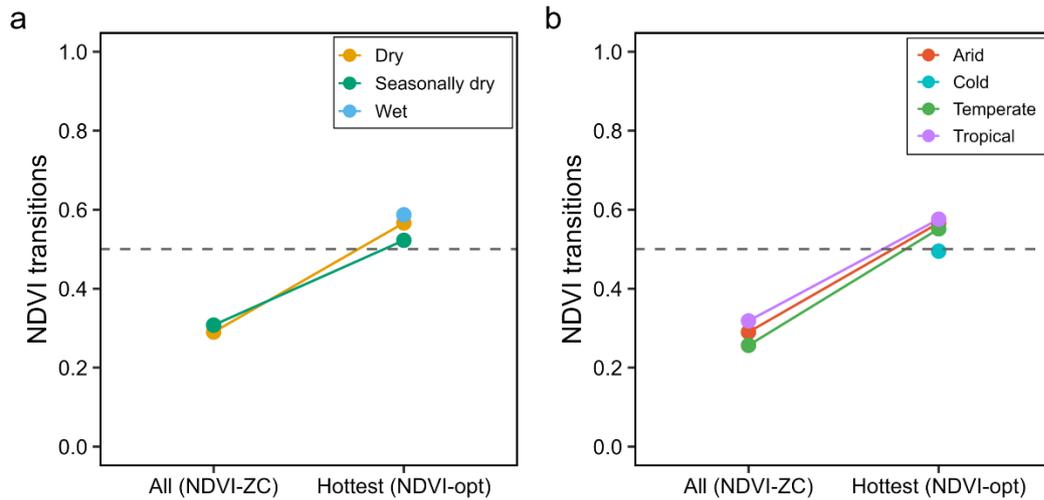
Supplementary Figure S14 | Distributions of NDVI zero-crossing (NDVI-ZC) transitions across cities. NDVI-ZC represents the vegetation greenness (NDVI) at which GAMM-predicted ΔLST transitions from neutral or warming effects to net surface cooling. NDVI-ZC was identified by linear interpolation at the point where predicted ΔLST crossed zero. Distributions summarise variability across cities within each group. Embedded boxplots within the violin plots indicate the median and interquartile range. The horizontal dashed line indicates NDVI-ZC = 0.2 as a reference level of relatively sparse vegetation cover.
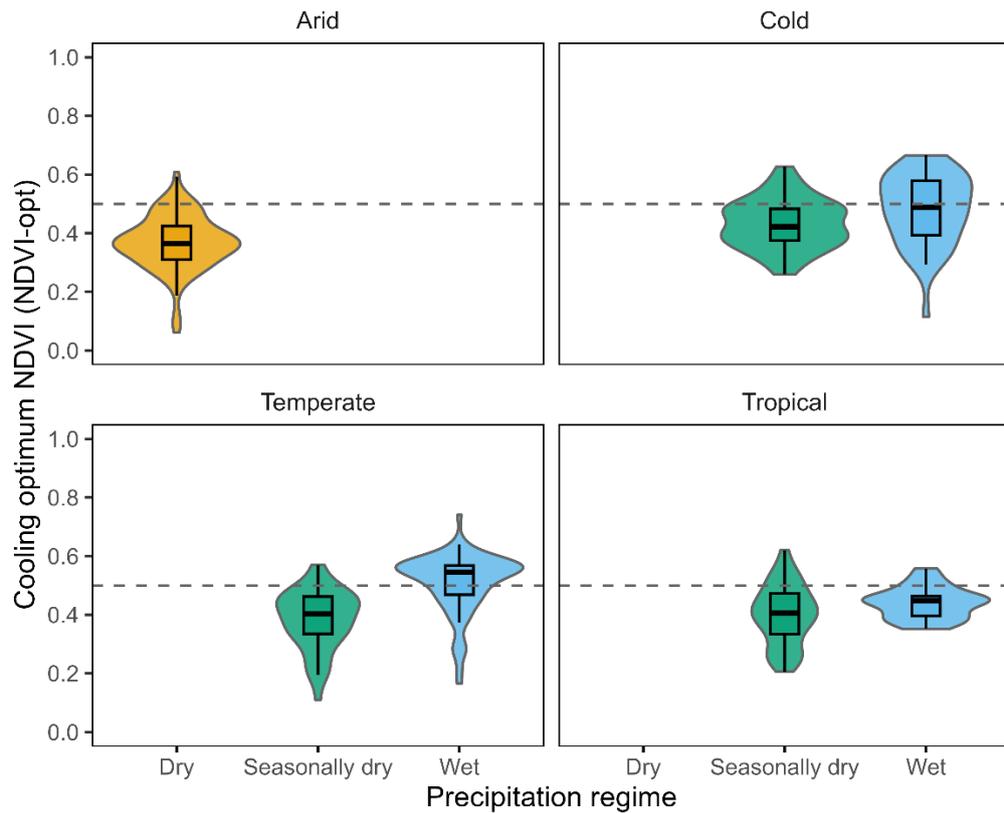
Supplementary Figure S15 | Distributions of NDVI optimum (NDVI-opt) across cities. NDVI-opt represents the vegetation greenness (NDVI) at which GAMM-predicted ΔLST reaches its most negative values (maximum cooling efficiency), estimated using observations from the hottest 10% observations based on background LST. Distributions summarise variability across cities within each group. Embedded boxes within the violin plots indicate the median and interquartile range. The horizontal dashed line indicates NDVI-opt = 0.5 as a reference level of relatively dense vegetation cover.

Supplementary Table S9 | Cooling onset and optimal greenness transitions across precipitation, climate and UGS groups. The table reports NDVI zero-crossing values (NDVI-ZC), defined as the NDVI at which GAMM-predicted ΔLST transitions from positive or neutral to negative values and NDVI optimal greenness values (NDVI-opt), defined as the NDVI associated with its most negative predicted ΔLST (maximum cooling efficiency). Values are reported for each precipitation regime, climate zone and urban green space (UGS) type. When the GAMM-predicted ΔLST remained negative across the full NDVI range, indicating persistent cooling with no zero crossing, NDVI-ZC was recorded as NA.

| Group	Sub-group	NDVI-ZC	NDVI-opt	
Precipitation regime	Dry		0.290	0.566
	Seasonally dry		0.308	0.522
	Wet	NA		0.587
Climate zone	Arid		0.290	0.566
	Cold	NA		0.495
	Temperate		0.257	0.552
	Tropical		0.318	0.576
UGS type	Sparse		0.290	0.430
	Open Veg		0.341	0.608
	Woody		0.257	0.580
	Hydric	NA		0.462

Supplementary Figure S16 | NDVI transitions under baseline and extreme heat conditions. Baseline cooling onset (NDVI-ZC) and cooling optimum (NDVI-opt) were derived from all observations (n = 84,290) and from extreme heat conditions (defined as the hottest 10% of observations based on background land surface temperature; n = 8,429), respectively. NDVI-ZC represents the NDVI at which GAMM-predicted ΔLST crosses zero, marking the transition from neutral or warming effects to net surface cooling, whereas NDVI-opt denotes the NDVI at which predicted ΔLST reaches its most negative (maximum cooling intensity) under extreme heat. Points indicate median transition values for **a)** precipitation regimes and **b)** climate zones, with lines connecting baseline and extreme heat estimates to illustrate shifts in cooling transitions. For some regimes, including wet and cold, predicted ΔLST remained negative across the full NDVI range and no zero crossing was identified, indicating persistent cooling. NDVI-ZC for these regimes was therefore not defined and only extreme-heat conditions are shown. Horizontal dashed lines indicate NDVI = 0.5 as a reference level of relatively dense vegetation cover.
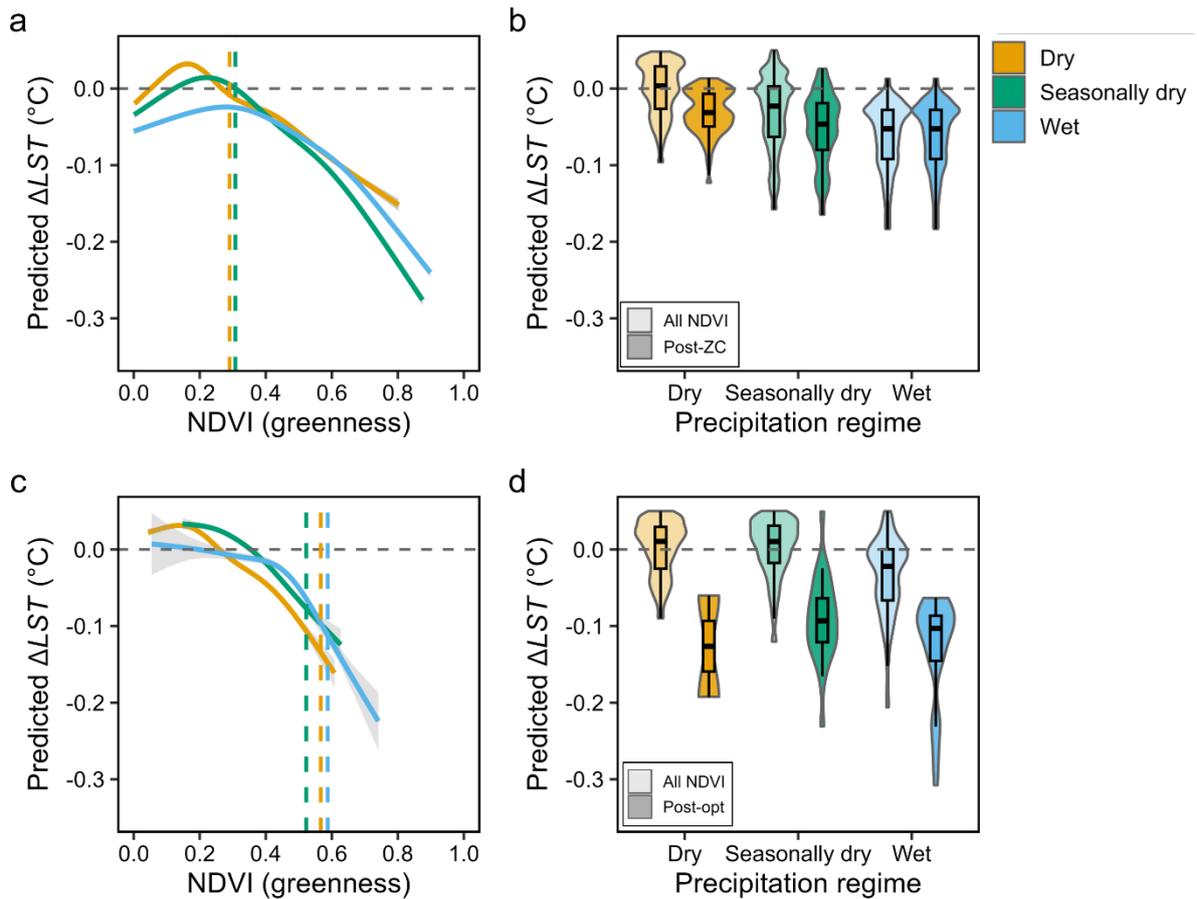
Supplementary Figure S17 | Cooling onset and post-transition cooling across precipitation regimes under baseline and extreme heat conditions. Generalised additive mixed model (GAMM) predictions are shown for all observations (**a-b**; n = 84,290) and for extreme heat conditions, defined as the hottest 10% of observations based on background land surface temperature (LST, °C) at each site (**c-d**; n = 8,429). In panels **a** and **c**, curves represent smoothed trends of ΔLST 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. Horizontal dashed line marks ΔLST = 0 °C. Vertical dashed lines indicate **a)** the baseline cooling onset (NDVI-ZC) and **c)** the cooling optimum (NDVI-opt) under extreme heat. In wet regime, no NDVI-ZC was identified as the GAMM-predicted ΔLST remained negative across the full NDVI range, indicating persistent cooling. Panels **b** and **d** show distributions of predicted ΔLST across precipitation regimes for all NDVI values (lighter colours) and for NDVI exceeding the regime-specific transitions (darker colours; post-ZC in **b** and post-opt in **d**).
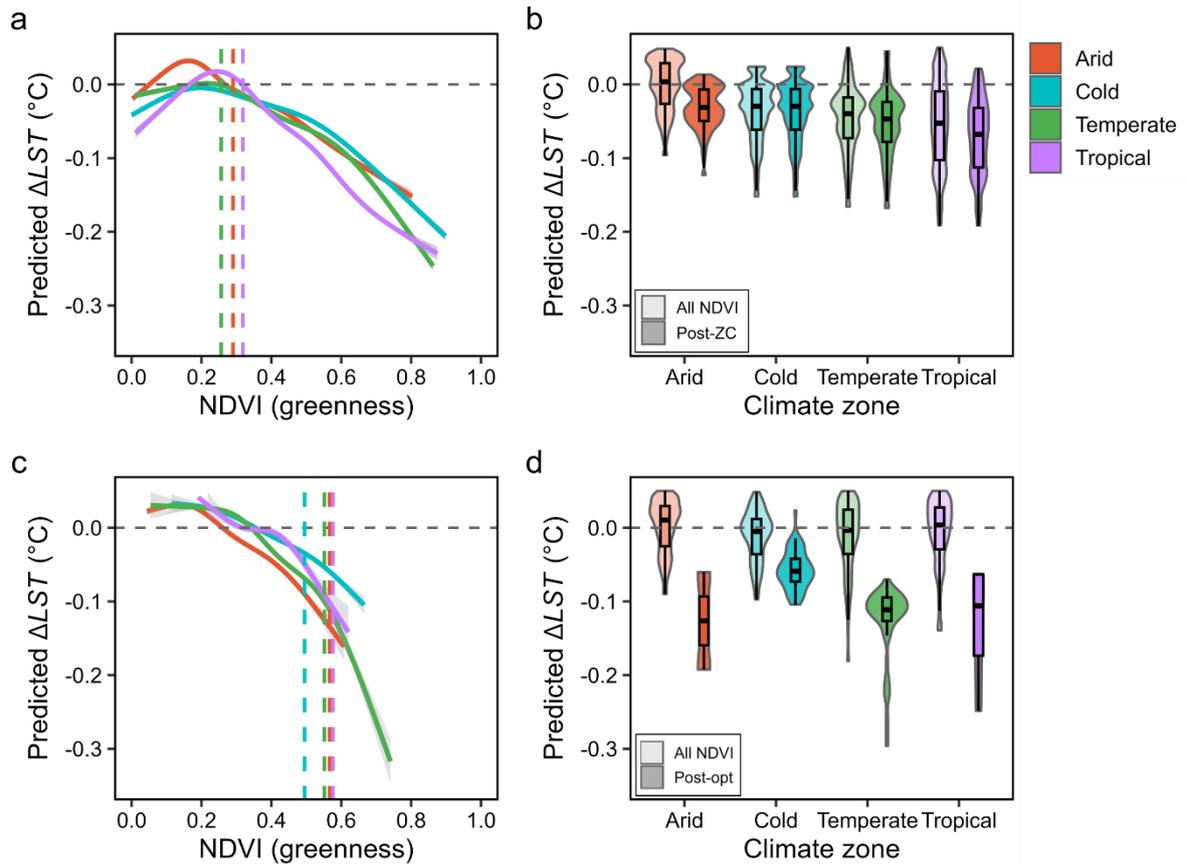
Supplementary Figure S18 | Cooling onset and post-transition cooling across climate zones under baseline and extreme heat conditions. Generalised additive mixed model (GAMM) predictions are shown for all observations (a-b; n = 84,290) and for extreme heat conditions, defined as the hottest 10% of observations based on background land surface temperature (LST, °C) at each site (c-d; n = 8,429). In panels **a** and **c**, curves represent smoothed trends of ΔLST values predicted by the fitted GAMM across NDVI within each climate zone. Shaded ribbons indicate 95% confidence intervals of the secondary smoothing applied to model predictions. Horizontal dashed line marks ΔLST = 0 °C. Vertical dashed lines indicate **a)** the baseline cooling onset (NDVI-ZC) and **c)** the cooling optimum (NDVI-opt) under extreme heat. In a cold climate, no NDVI-ZC was identified as the GAMM-predicted ΔLST remained negative across the full NDVI range, indicating persistent cooling. Panels **b** and **d** show distributions of predicted ΔLST across climate zones for all NDVI values (lighter colours) and for NDVI exceeding the climate-specific transitions (darker colours; post-ZC in **b** and post-opt in **d**).
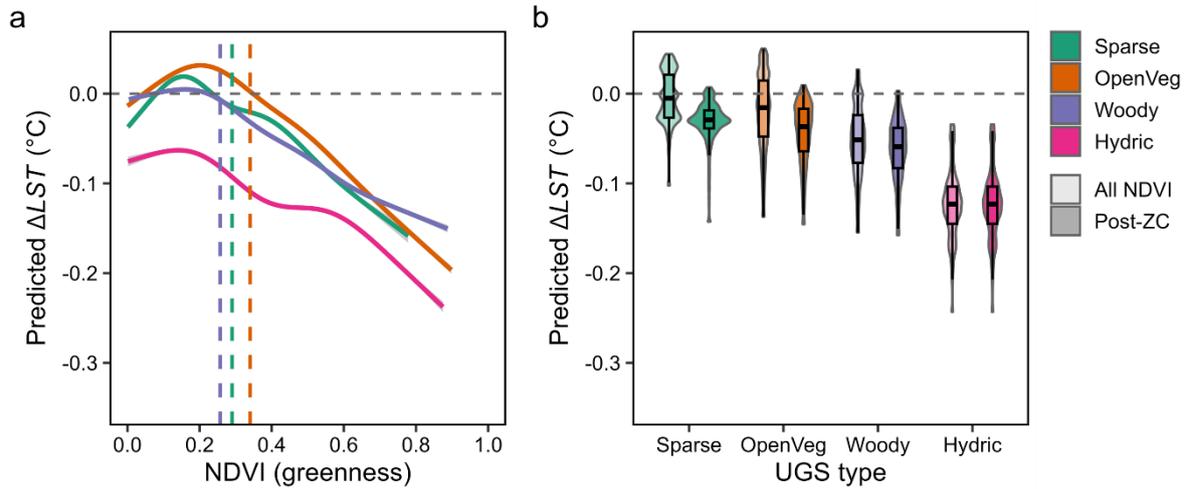
Supplementary Figure S19 | Cooling onset transitions across UGS type. a) Generalised additive mixed model (GAMM) predictions are shown for all observations (a-b; n = 84,290) and for extreme heat conditions, defined as the hottest 10% of observations based on background land surface temperature (LST, °C) at each site (c-d; n = 8,429). Curves represent smoothed trends of ΔLST values predicted by the fitted GAMM across NDVI within each UGS type. 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 type, the greenness level at which ΔLST transitions from warming or neutral to net surface cooling. In a hydric UGS type, no NDVI-ZC was identified as the GAMM-predicted ΔLST remained negative across the full NDVI range, indicating persistent cooling. **b)** Distributions of predicted ΔLST across UGS type for all NDVI values (lighter colours) and for NDVI exceeding the climate-specific transitions (darker colours). In all panels, horizontal dashed lines mark ΔLST = 0 °C.
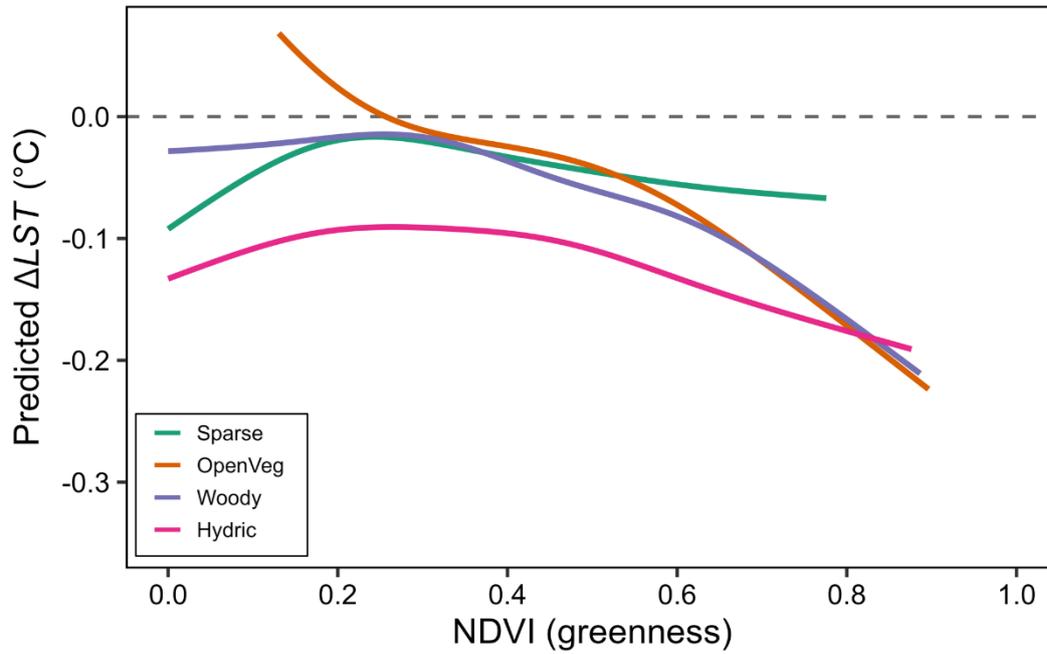
Supplementary Figure S20 | Partial effects of vegetation greenness on urban cooling by UGS type under an illustrative hydroclimatic condition (Temperate-Wet). Predicted relationships between NDVI (vegetation greenness) and ΔLST (difference in land surface temperature between urban green and grey areas; °C) are shown for different urban green space (UGS) types, derived from the full generalized additive mixed model (GAMM). Predictions were evaluated under the temperate-wet climate as an illustrative hydroclimatic condition, with latitude and longitude held at their median values and other covariates fixed. Coloured lines indicate model-predicted partial effects of NDVI, with values masked outside the observed NDVI range for each UGS type to avoid extrapolation. The horizontal dashed line marks ΔLST = 0 °C.
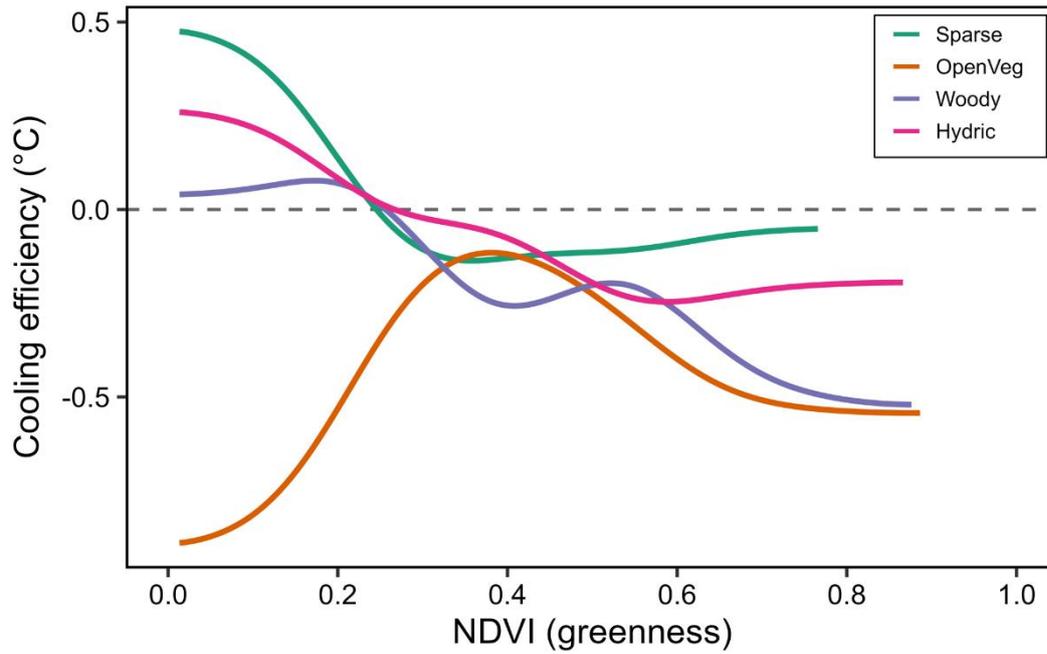
Supplementary Figure S21 | Cooling efficiency curves by UGS type under an illustrative hydroclimatic condition (Temperate-Wet). An illustrative cooling efficiency (°C; temperate-wet regimes) is shown as the marginal change in predicted ΔLST (difference in land surface temperature between urban green and grey areas) per unit increase in NDVI (°C per NDVI unit). Predictions were calculated as the first derivative of the partial NDVI–ΔLST relationships from the full GAMM (Supplementary Fig. S20). Curves are presented separately for each urban green space (UGS) type while all other covariates, including hydroclimate, spatial location, and model offsets, are held constant at temperate-wet reference values. Negative values indicate increasing cooling with additional greenness, whereas values approaching zero denote diminishing marginal cooling gains. The horizontal dashed line indicates cooling efficiency = 0 °C.
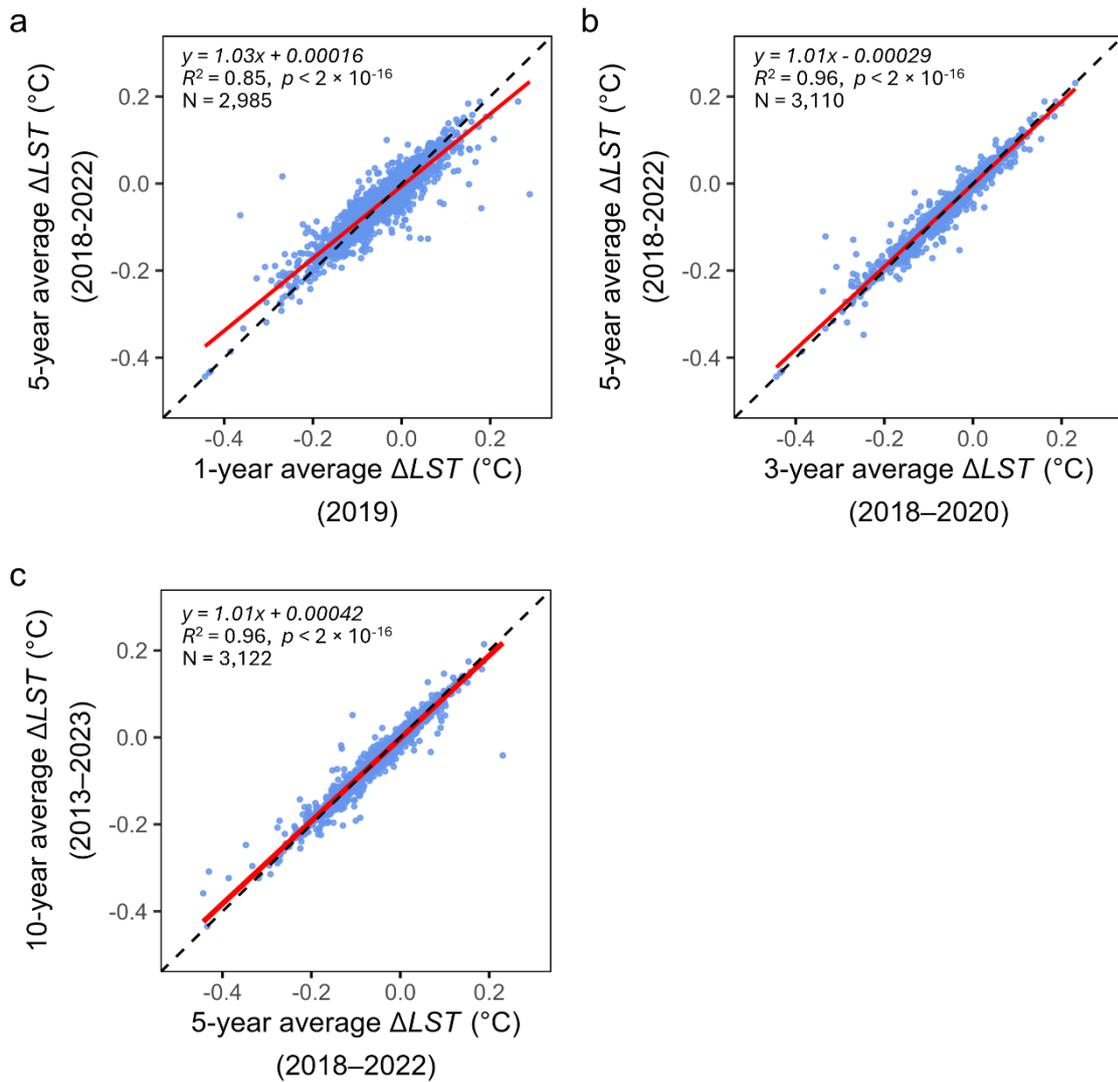
Supplementary Figure S22 | Consistency of normalized ΔLST across temporal windows (1-, 3- and 10-year subsets). Scatterplots compare ΔLST (difference in land surface temperature, LST; °C) averaged over different temporal spans. **a)** 1-year (2019), **b)** 3-year (2018–2020) and **c)** 10-year (2013–2023) periods, compared with the 5-year baseline (2018–2022). Normalized ΔLST values show highly consistent patterns across all temporal windows, demonstrating the robustness of the 5-year dataset used in the main analyses. Reported p-values correspond to the significance of the slope coefficients from the fitted linear models (two-sided t-tests), alongside sample sizes (N) and coefficients of determination (R^2).

Supplementary Table S10 | Testing for sensitivity to NDVI discretisation. The table reports the cooling onset (NDVI-ZC), defined as the NDVI values at which GAMM-predicted ΔLST transitions from neutral or warming conditions to net surface cooling. A sensitivity test was assessed using discretised continuous NDVI derived from Landsat observations with fixed-width bins (0.02 and 0.05), while retaining the original continuous specification for the main analysis. Values are reported for each precipitation regime, climate zone and urban green space (UGS) type. When the GAMM-predicted ΔLST remained negative across the full NDVI range, indicating persistent cooling with no zero crossing, NDVI-ZC was recorded as NA.

Group	Sub-group	NDVI-ZC	
NDVI bin width = 0.02			
Precipitation regime	Dry		0.289
	Seasonally dry		0.295
	Wet	NA	
Climate zone	Arid		0.289
	Cold	NA	
	Temperate		0.208
	Tropical		0.324
UGS type	Sparse		0.289
	Open Veg		0.334
	Woody		0.244
	Hydric	NA	
NDVI bin width = 0.05			
Precipitation regime	Dry		0.278
	Seasonally dry		0.279
	Wet	NA	
Climate zone	Arid		0.278
	Cold	NA	
	Temperate		0.197
	Tropical		0.308
UGS type	Sparse		0.278
	Open Veg		0.318
	Woody		0.225
	Hydric	NA	

**Supplementary Table S11 | Testing for robustness to alternative NDVI product (MODIS) and spatial scales of buffered NDVI greenness.** The table reports the cooling onset (NDVI-ZC), defined as the NDVI values at which GAMM-predicted ΔLST transitions from neutral or warming conditions to net surface cooling. Robustness tests were conducted using i) NDVI derived from MODIS observations over the same study period (2018-2022) and ii) NDVI calculated within alternative buffer radii (3 km and 10 km) from the centroid of urban polygons to evaluate sensitivity to the spatial definition of greenness. Values are reported for each precipitation regime, climate zone and urban green space (UGS) type. When the GAMM-predicted ΔLST remained negative across the full NDVI range, indicating persistent cooling with no zero crossing, NDVI-ZC was recorded as NA.

Group	Sub-group	NDVI-ZC
MODIS NDVI		
Precipitation regime	Dry	0.315
	Seasonally dry	0.283
	Wet	NA
Climate zone	Arid	0.315
	Cold	NA
	Temperate	0.262
	Tropical	0.242
UGS type	Sparse	0.283
	Open Veg	0.358
	Woody	0.204
	Hydric	NA
Spatial buffer radius = 3 km		
Precipitation regime	Dry	0.130
	Seasonally dry	0.132
	Wet	NA
Climate zone	Arid	0.130
	Cold	NA
	Temperate	0.111
	Tropical	0.131
UGS type	Sparse	0.118
	Open Veg	0.154
	Woody	0.126
	Hydric	NA
Spatial buffer radius = 10 km		
Precipitation regime	Dry	0.130
	Seasonally dry	0.124
	Wet	NA
Climate zone	Arid	0.130
	Cold	NA
	Temperate	0.106
	Tropical	0.148
UGS type	Sparse	0.101
	Open Veg	0.160
	Woody	0.130
	Hydric	NA
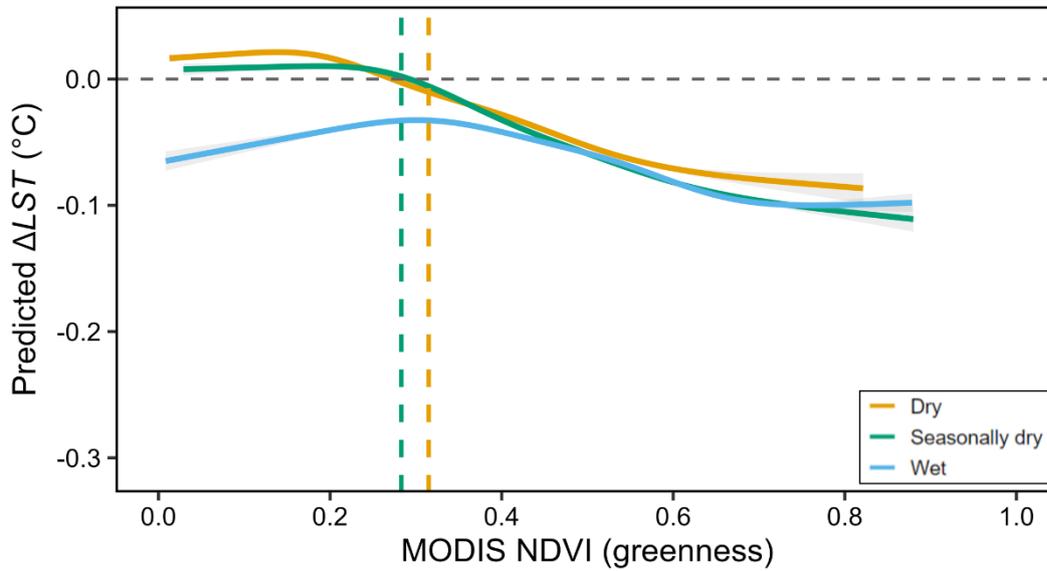
Supplementary Fig. S23 | Robustness test of greening transition to an alternative NDVI product (MODIS; 1km, 16 days). Predicted change in ΔLST (difference in land surface temperature between urban green and grey spaces; °C) as a function of vegetation greenness derived from MODIS NDVI for the period 2018-2022. Curves show GAMM-predicted NDVI–ΔLST relationships for dry, seasonally dry and wet regimes, with shaded ribbons indicating standard errors. Vertical dashed lines indicate median cooling onset transition (NDVI-ZC) for dry and seasonally dry regimes; no NDVI-ZC is identified for wet regimes, which exhibit persistent cooling across the full observed NDVI range.
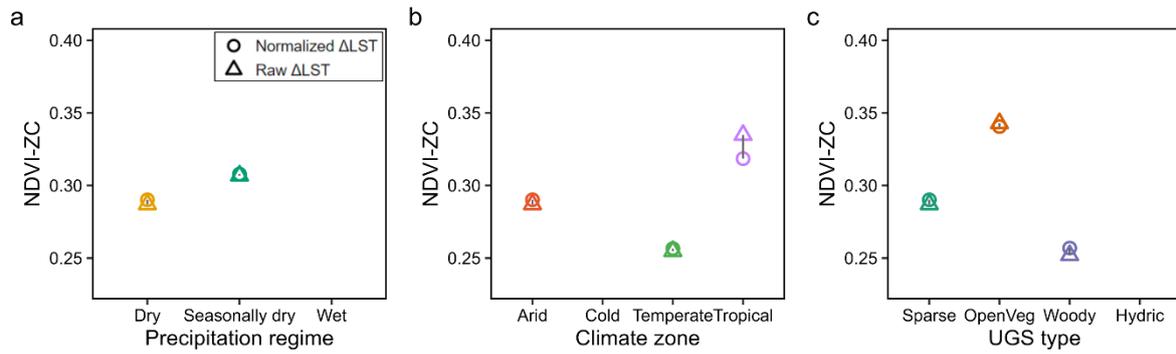
Supplementary Fig. S24 | Robustness of NDVI-ZC estimates to response transformation across grouping schemes. Comparison of cooling onset (NDVI-ZC) estimates derived from models fitted using normalized ΔLST and untransformed ΔLST (raw ΔLST) across **a)** precipitation regime, **b)** climate zone and **c)** UGS type. Points represent group-level NDVI-ZC estimates from each modelling approach. No NDVI-ZC points are shown for sub-groups such as wet regimes, cold climates and hydric UGS types, reflecting persistent cooling across the entire observed NDVI range. Estimates are closely aligned across transformation choices, indicating that inferred cooling onset patterns are not driven by the signed-log transformation of ΔLST.