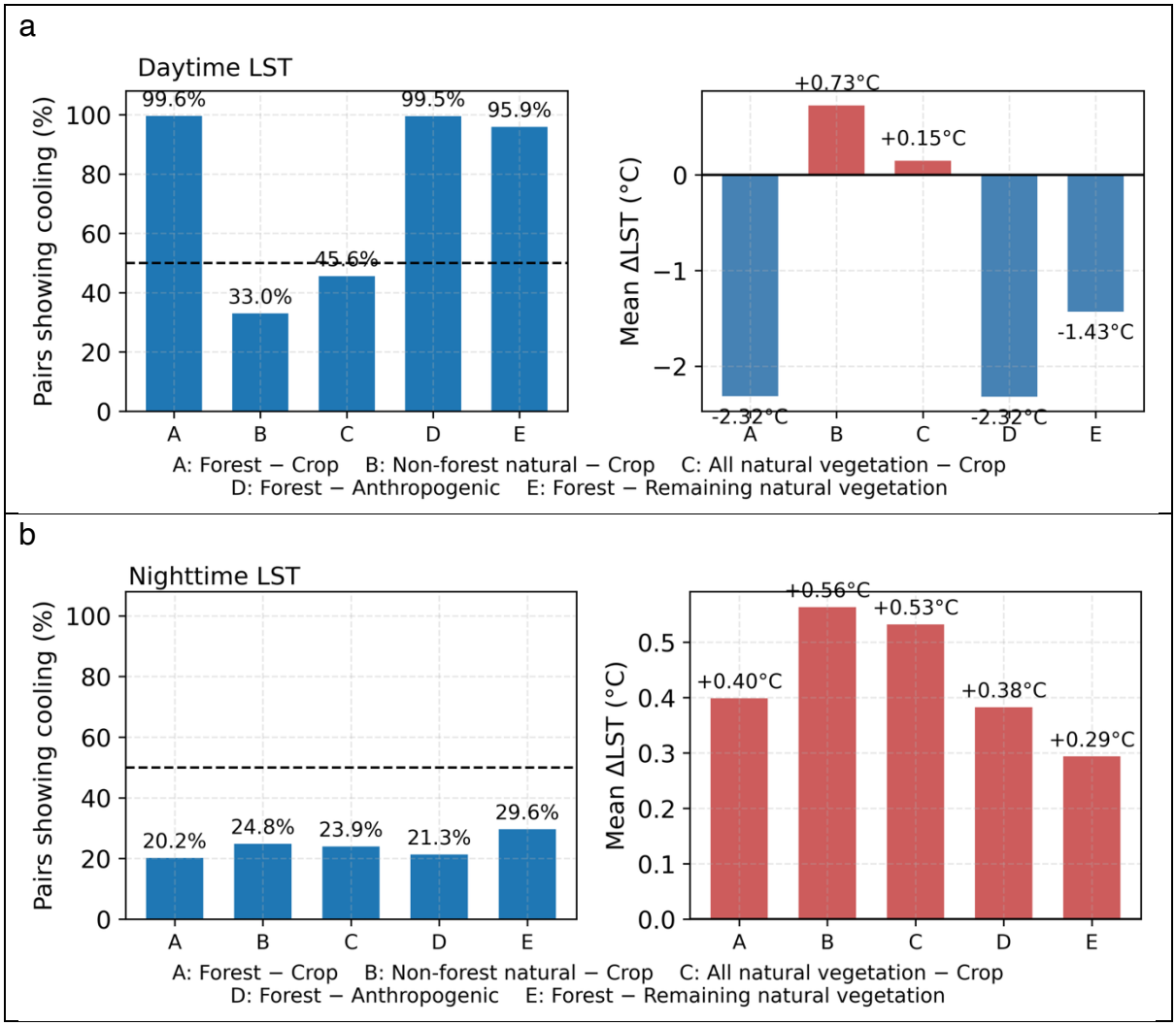
Supplementary Information for

Forest cooling is not natural-vegetation cooling: pair-specific and environmentally conditioned land-cover thermal contrasts across India

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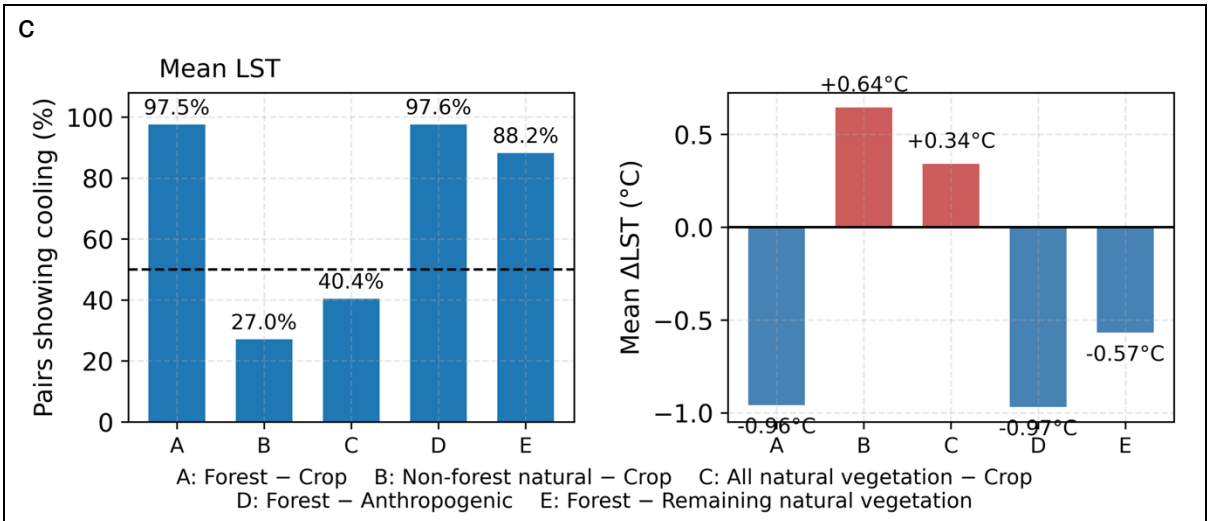


Fig. S1. Consistency and magnitude of land surface temperature responses across aggregated land-cover transition groups. The left panels show the percentage of land-cover pairs exhibiting cooling for daytime, nighttime and mean LST, with the dashed horizontal line indicating 50%. The right panels show the corresponding mean ΔLST (°C). Transition groups are A: Forest-Crop, B: Non-forest natural vegetation-Crop, C: All natural vegetation-Crop, D: Forest-Anthropogenic, and E: Forest-Remaining natural vegetation. Positive ΔLST indicates warming and negative ΔLST indicates cooling.

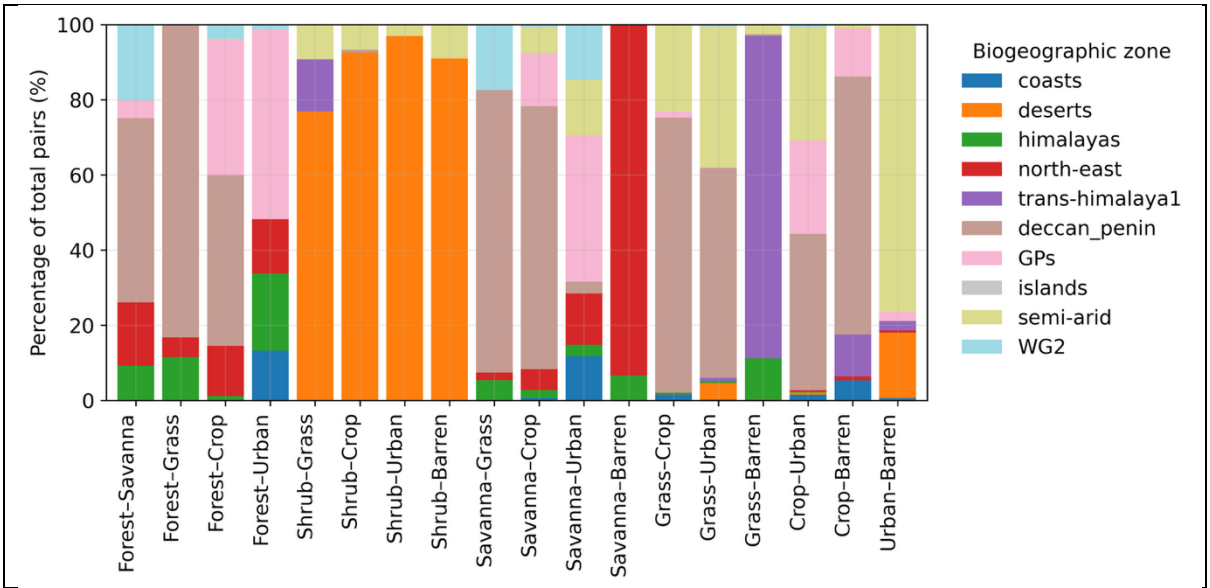


Fig. S2. Biogeographic-zone contributions to land-cover pair combinations across India. Stacked bars show the proportional contribution (%) of each biogeographic zone to the total number of valid grid-cell pairs for each land-cover (LC) combination. Differences in zone contributions reflect the geographical and ecological distributions of the respective LC classes.

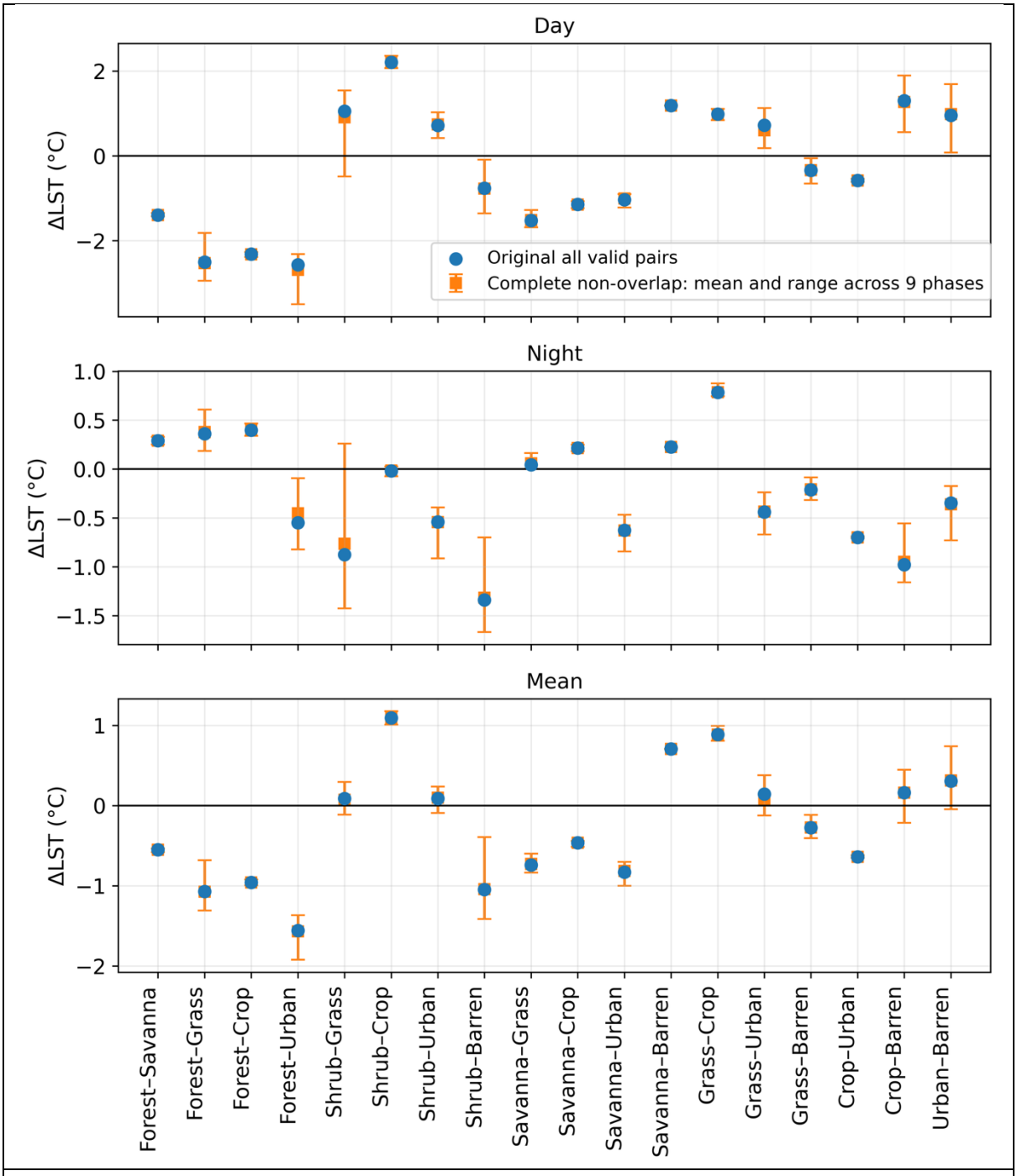


Fig. S3. Robustness of land surface temperature differences (ΔLST) to spatial thinning of overlapping moving-window samples. Comparison of ΔLST estimates obtained using all valid land-cover pairs (blue) and complete non-overlapping samples (orange) across nine spatial phases for daytime, nighttime, and mean LST conditions. Orange markers represent the mean estimate across the nine non-overlapping phases, with error bars showing the corresponding range. The horizontal black line denotes ΔLST = 0. The spatial-thinning procedure constructs nine complete non-overlapping phase combinations from the original overlapping moving-window sampling design.

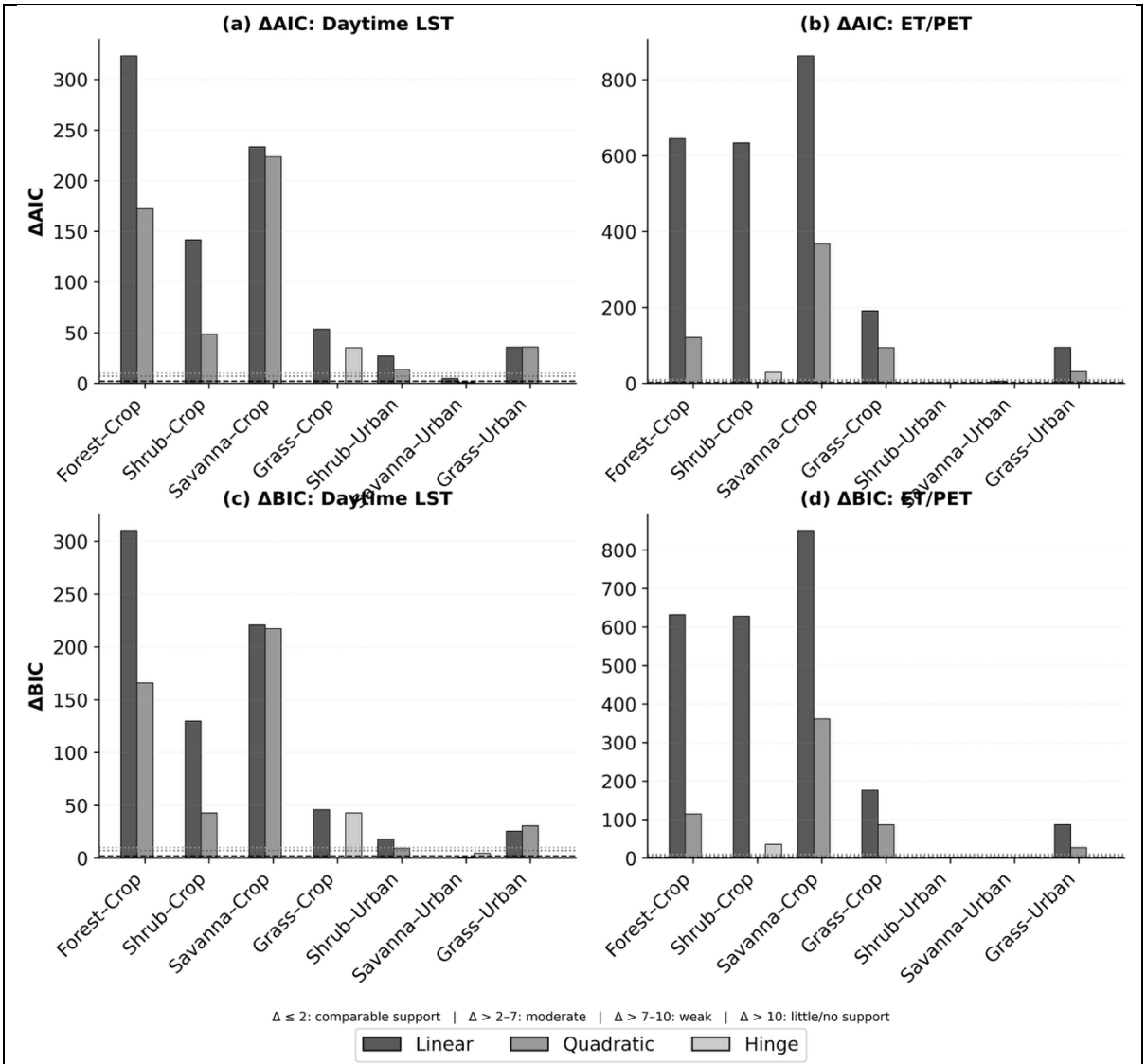


Fig. S4. Comparison of alternative functional forms for modelling daytime land surface temperature and evapotranspiration-to-potential-evapotranspiration ratio (ET/PET) across major land-cover transitions. Differences in Akaike Information Criterion (ΔAIC; a-b) and Bayesian Information Criterion (ΔBIC; c-d) are shown for linear, quadratic, and hinge models. Smaller ΔAIC and ΔBIC values indicate stronger relative support for a candidate model, while increasing differences indicate progressively weaker support.

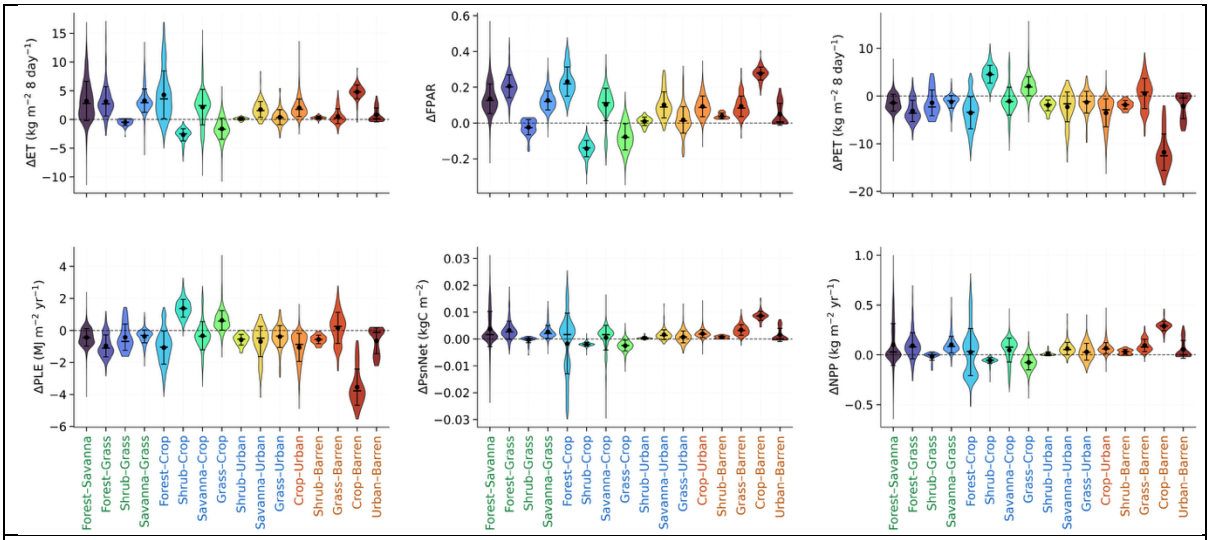
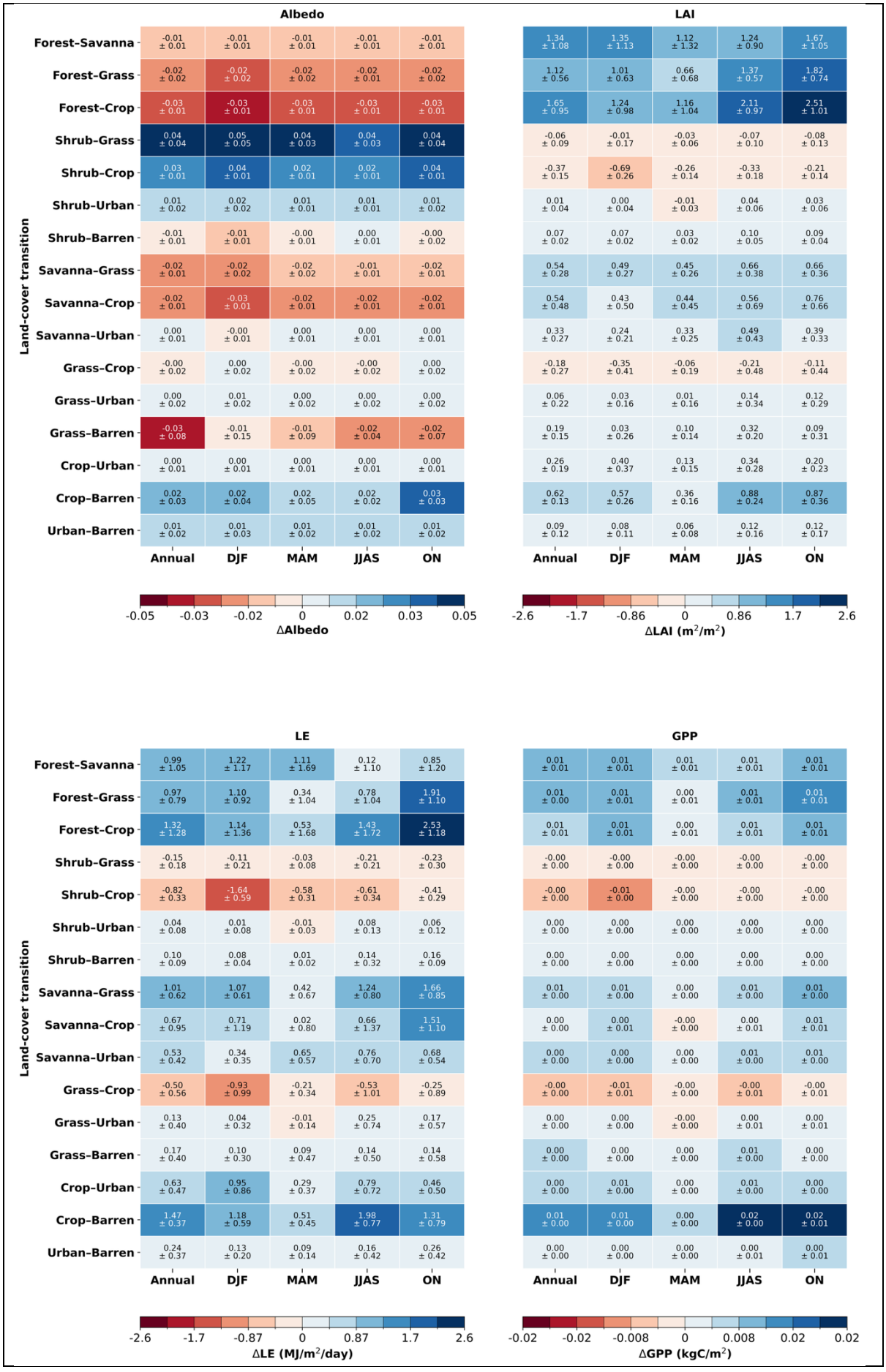


Fig. S5. Distributions of land-surface biophysical changes associated with land-cover transitions across India. Violin plots show the distribution of changes in key surface-energy and vegetation variables for the analysed land-cover transition pairs. The width of each violin represents the relative density of observations, allowing comparison of the magnitude, variability, and direction of biophysical responses among transitions.


Albedo
LAI
LE
GPP
Land-cover transition
Forest-Savanna
Forest-Grass
Forest-Crop
Shrub-Grass
Shrub-Crop
Shrub-Urban
Shrub-Barren
Savanna-Grass
Savanna-Crop
Savanna-Urban
Grass-Crop
Grass-Urban
Grass-Barren
Crop-Urban
Crop-Barren
Urban-Barren
Annual
DJF
MAM
JJAS
ON
-0.05 -0.03 -0.02 0 0.02 0.03 0.05
ΔAlbedo
-2.6 -1.7 -0.86 0 0.86 1.7 2.6
ΔLAI (m²/m²)
-2.6 -1.7 -0.87 0 0.87 1.7 2.6
ΔLE (MJ/m²/day)
-0.02 -0.02 -0.008 0 0.008 0.02 0.02
ΔGPP (kgC/m²)

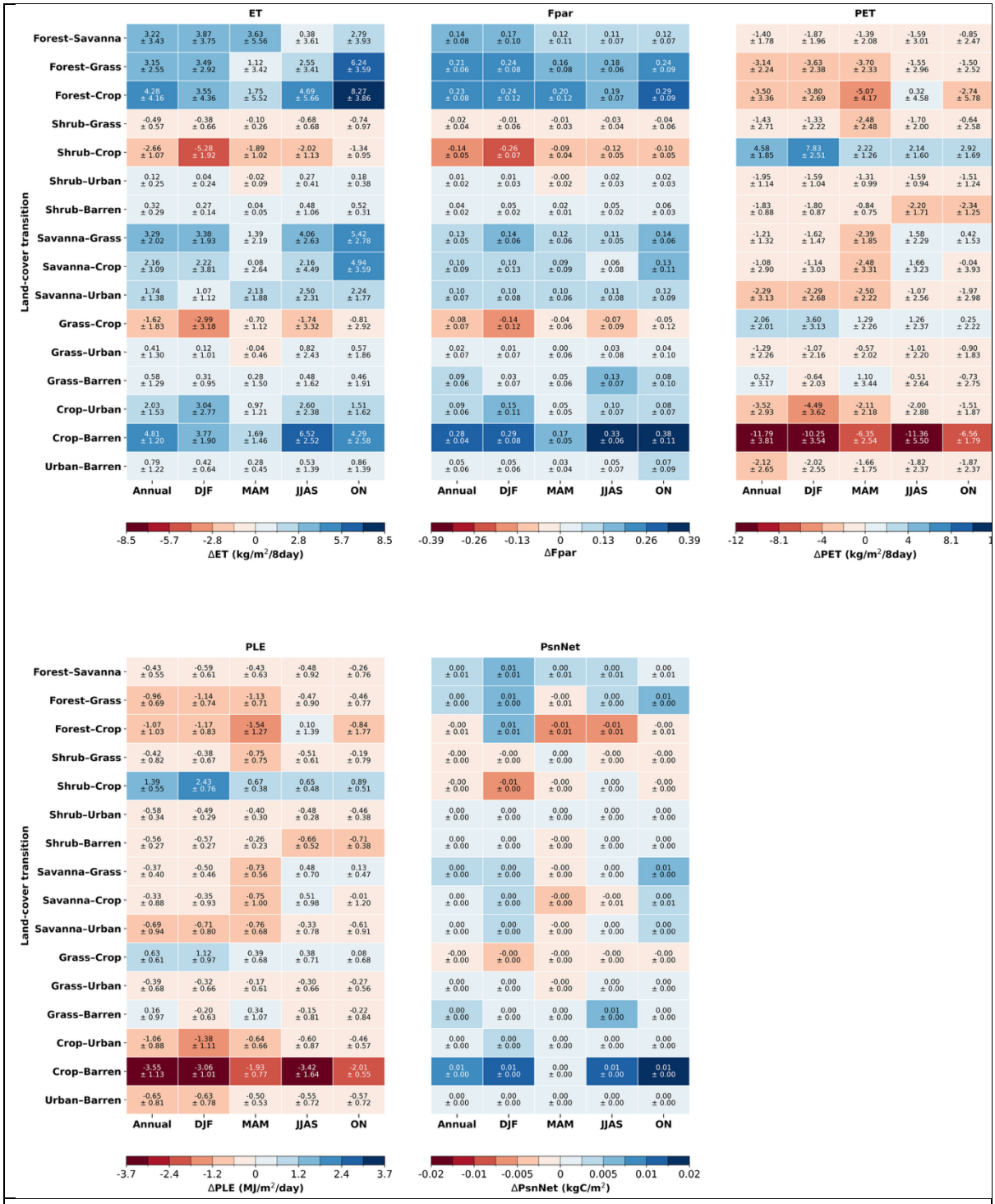
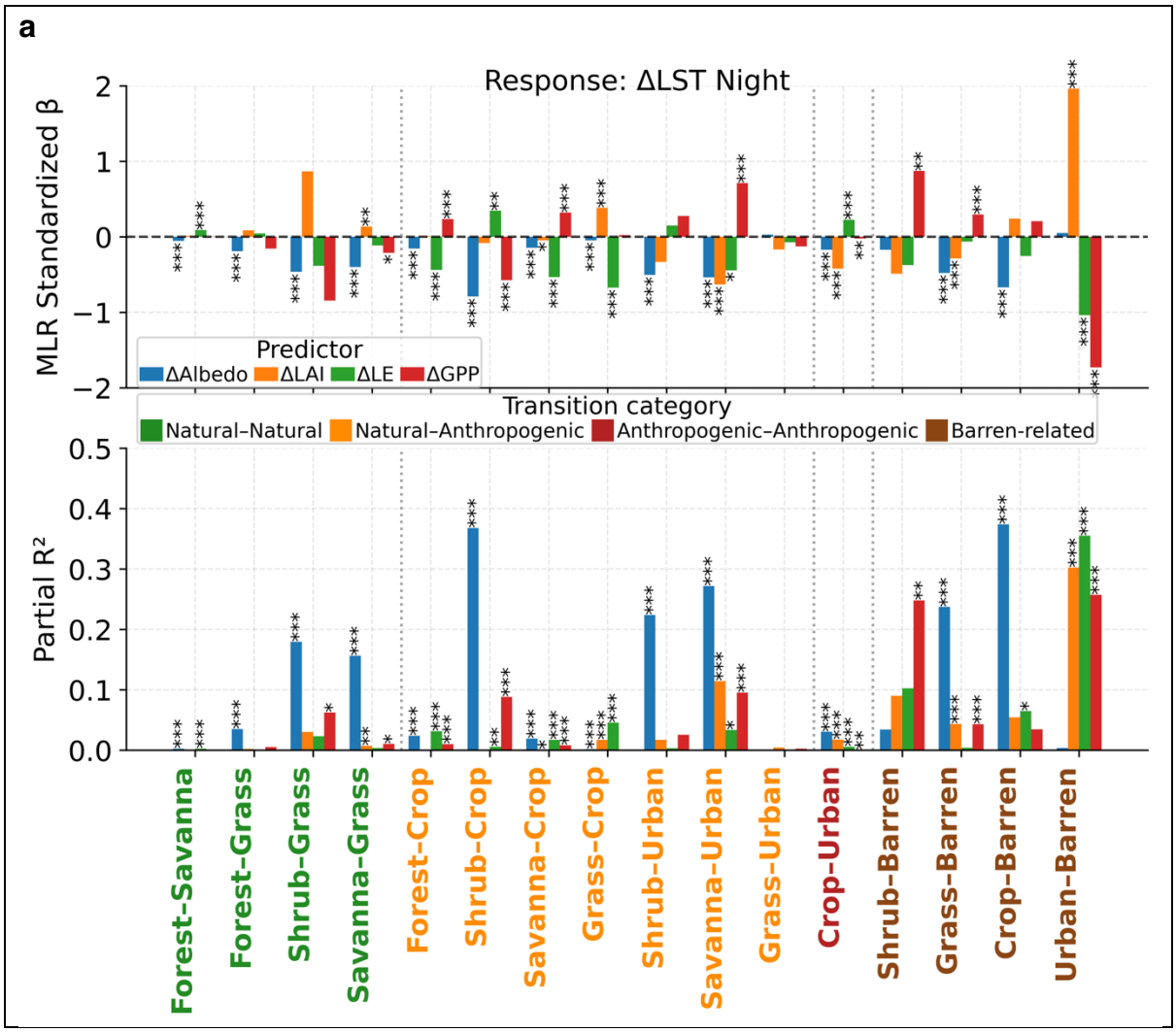
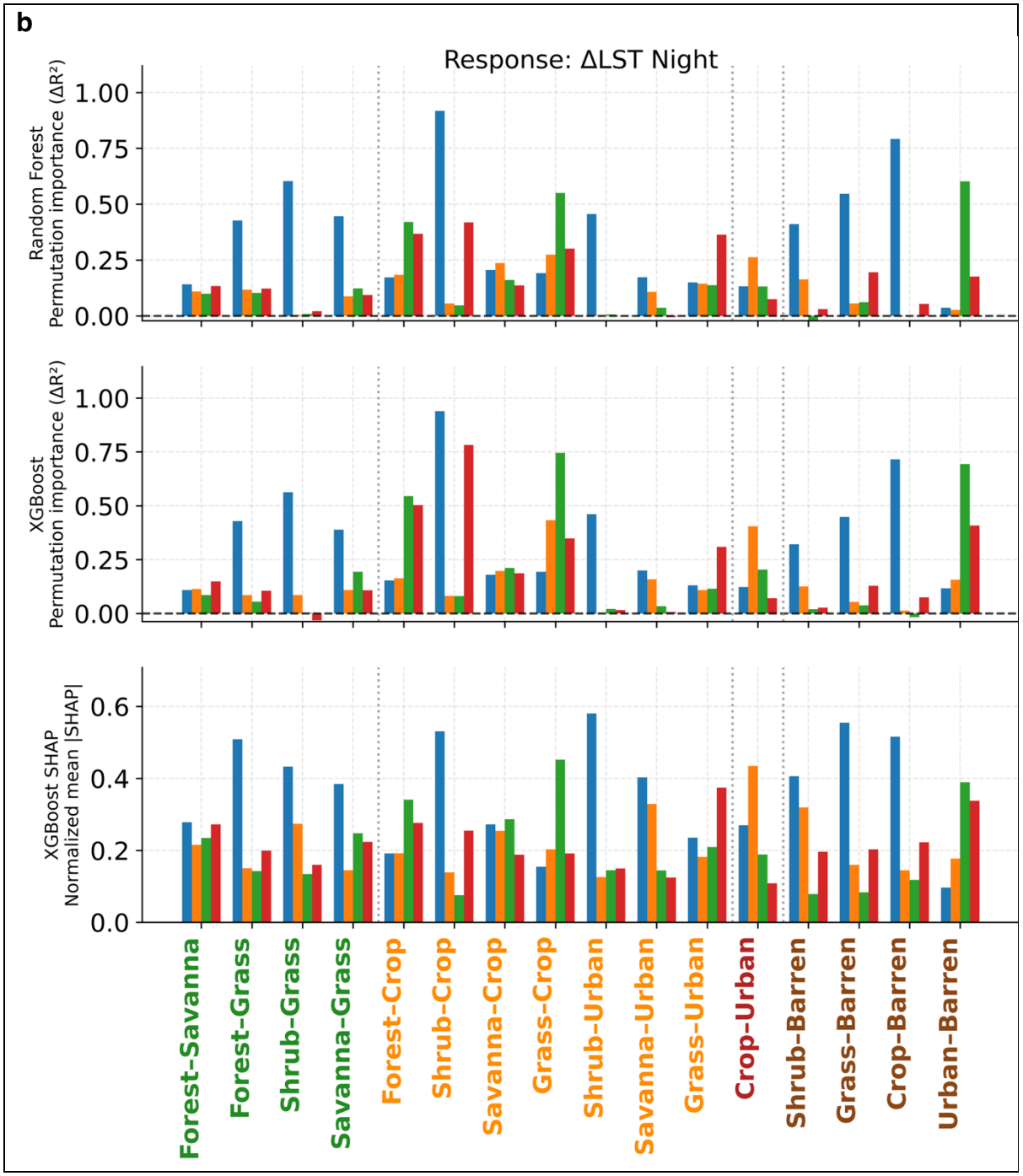


Fig. S6. Annual and seasonal changes in land-surface biophysical and hydrological variables associated with land-cover transitions. Heatmaps show changes in albedo, leaf area index (LAI), latent heat flux (LE), gross primary productivity (GPP), evapotranspiration (ET), fraction of photosynthetically active radiation (FPar), potential evapotranspiration (PET), potential latent heat flux (PLE), and net photosynthesis (PsnNet) associated with each land-cover transition. Columns represent annual conditions and the DJF, MAM, JJAS, and ON seasons. Cell values indicate the estimated change for each land-cover transition-season combination, while the diverging colour scales represent the direction and magnitude of the response.


a
Response: ΔLST Night
MLR Standardized β
Predictor
ΔAlbedo
ΔLAI
ΔLE
ΔGPP
Transition category
Natural–Natural
Natural–Anthropogenic
Anthropogenic–Anthropogenic
Barren-related
Partial R²
Forest–Savanna
Forest–Grass
Shrub–Grass
Savanna–Grass
Forest–Crop
Shrub–Crop
Savanna–Crop
Grass–Crop
Shrub–Urban
Savanna–Urban
Grass–Urban
Crop–Urban
Shrub–Barren
Grass–Barren
Crop–Barren
Urban–Barren


b
Response: ΔLST Night
Random Forest
Permutation importance (ΔR²)
1.00
0.75
0.50
0.25
0.00
XGBoost
Permutation importance (ΔR²)
1.00
0.75
0.50
0.25
0.00
XGBoost SHAP
Normalized mean |SHAP|
0.6
0.4
0.2
0.0
Forest–Savanna
Forest–Grass
Shrub–Grass
Savanna–Grass
Forest–Crop
Shrub–Crop
Savanna–Crop
Grass–Crop
Shrub–Urban
Savanna–Urban
Grass–Urban
Crop–Urban
Shrub–Barren
Grass–Barren
Crop–Barren
Urban–Barren

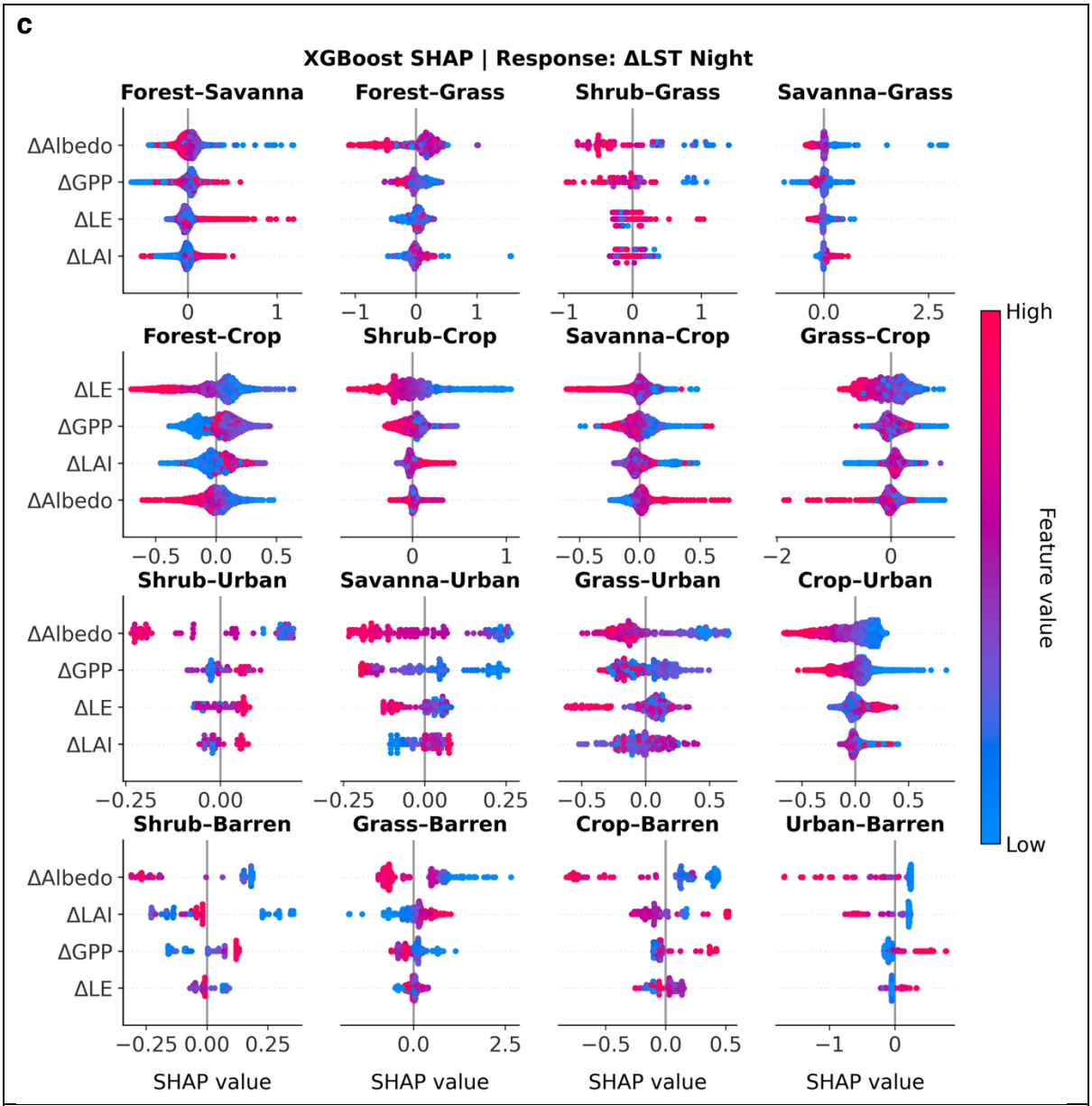
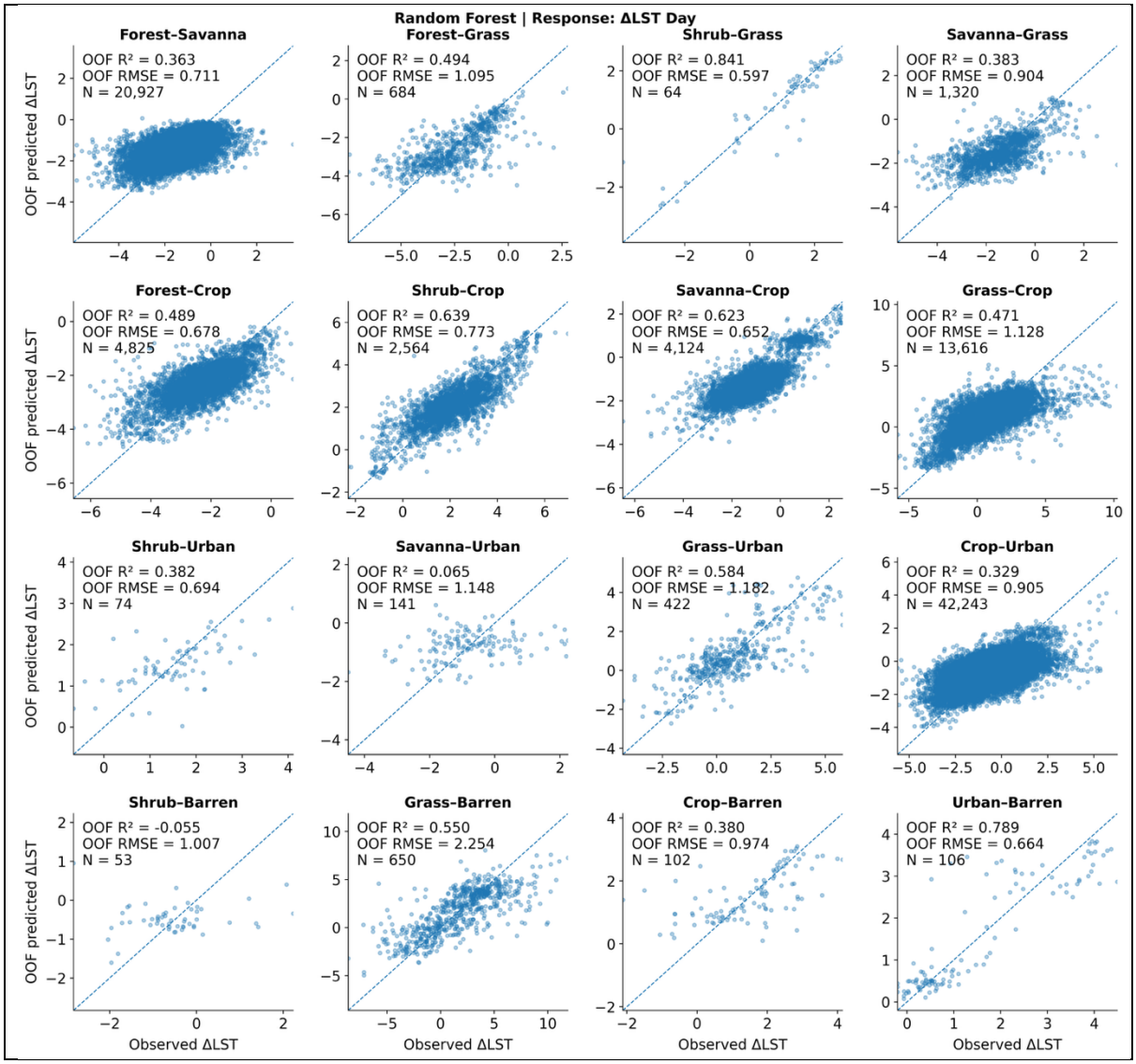
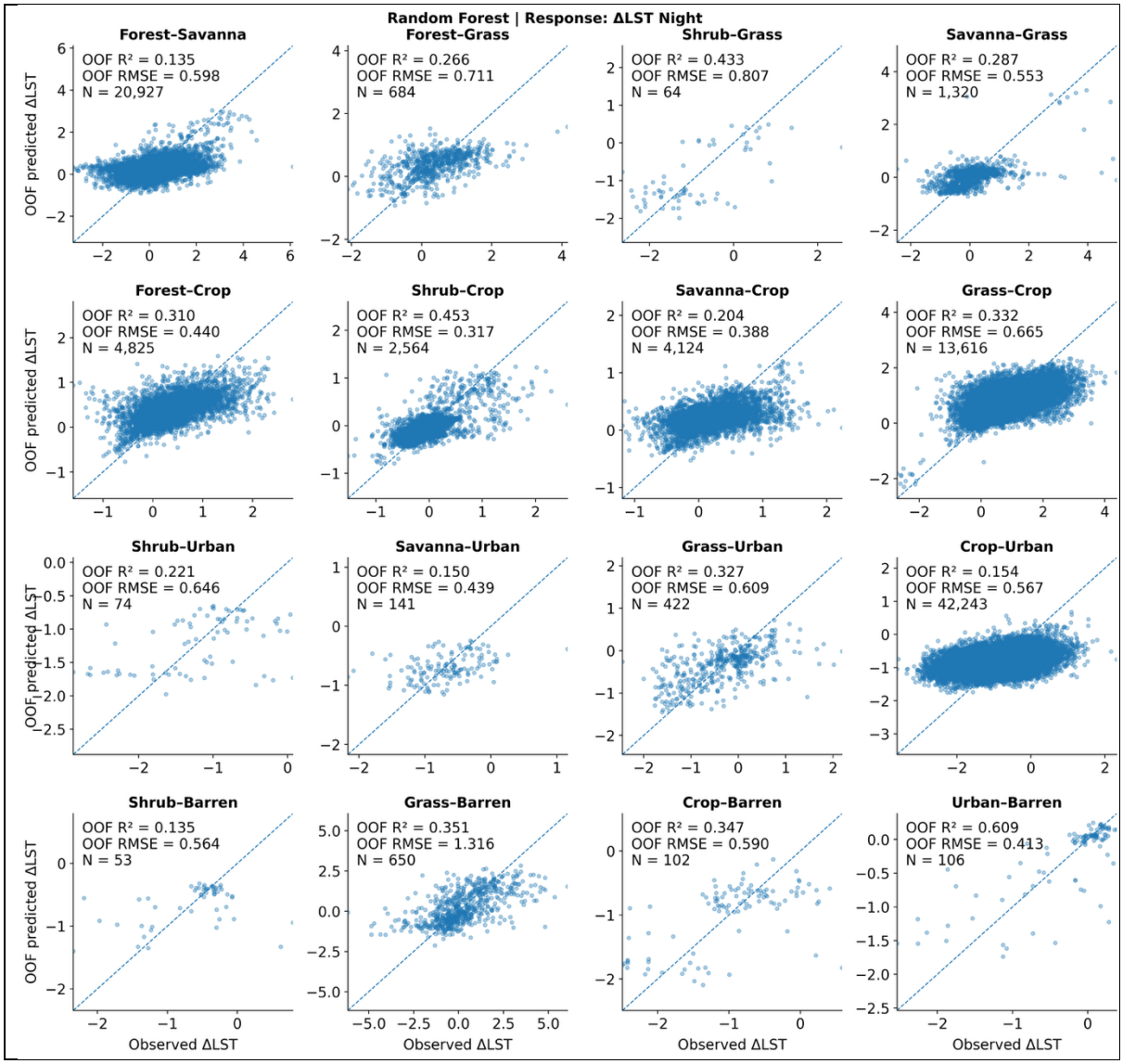
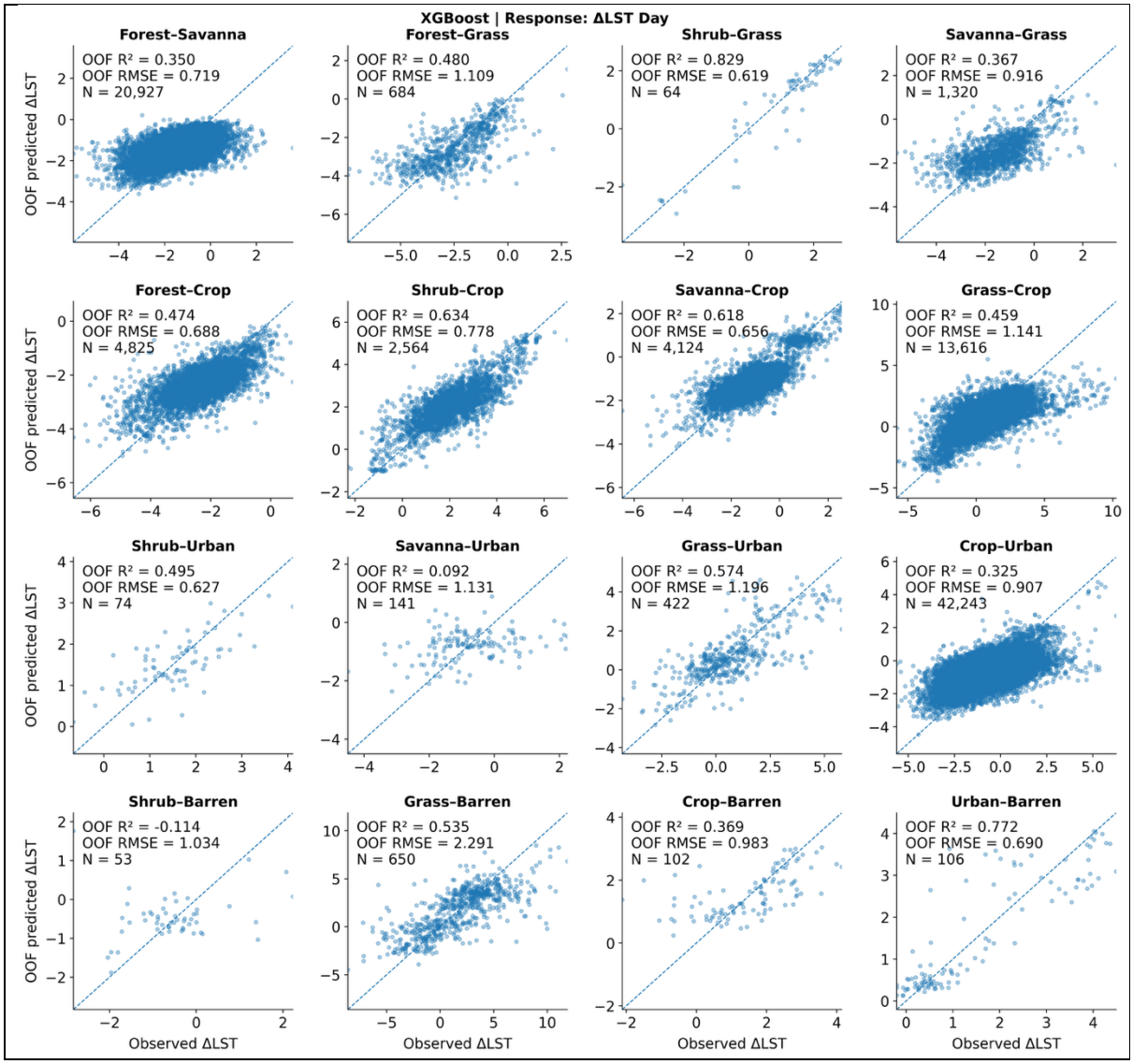


Fig. S7. Relative importance and effects of biophysical predictors in explaining nighttime land surface temperature differences (ΔLST) among land-cover transitions. The upper panel shows standardized coefficients (β) from multiple linear regression (MLR), with corresponding partial R^2 values in the lower panel for ΔAlbedo, ΔLAI, ΔLE, and ΔGPP. The subsequent permutation-importance panels compare predictor importance derived from Random Forest and XGBoost models, together with normalized mean absolute SHAP importance for XGBoost. The SHAP summary plots show the direction and magnitude of individual predictor contributions to nighttime ΔLST for each land-cover transition; point colour represents relative feature value.


Random Forest | Response: ΔLST Day
Forest–Savanna
OOF R² = 0.363
OOF RMSE = 0.711
N = 20,927
Forest–Grass
OOF R² = 0.494
OOF RMSE = 1.095
N = 684
Shrub–Grass
OOF R² = 0.841
OOF RMSE = 0.597
N = 64
Savanna–Grass
OOF R² = 0.383
OOF RMSE = 0.904
N = 1,320
Forest–Crop
OOF R² = 0.489
OOF RMSE = 0.678
N = 4,825
Shrub–Crop
OOF R² = 0.639
OOF RMSE = 0.773
N = 2,564
Savanna–Crop
OOF R² = 0.623
OOF RMSE = 0.652
N = 4,124
Grass–Crop
OOF R² = 0.471
OOF RMSE = 1.128
N = 13,616
Shrub–Urban
OOF R² = 0.382
OOF RMSE = 0.694
N = 74
Savanna–Urban
OOF R² = 0.065
OOF RMSE = 1.148
N = 141
Grass–Urban
OOF R² = 0.584
OOF RMSE = 1.182
N = 422
Crop–Urban
OOF R² = 0.329
OOF RMSE = 0.905
N = 42,243
Shrub–Barren
OOF R² = -0.055
OOF RMSE = 1.007
N = 53
Grass–Barren
OOF R² = 0.550
OOF RMSE = 2.254
N = 650
Crop–Barren
OOF R² = 0.380
OOF RMSE = 0.974
N = 102
Urban–Barren
OOF R² = 0.789
OOF RMSE = 0.664
N = 106
OOF predicted ΔLST
Observed ΔLST


Random Forest | Response: ΔLST Night
Forest-Savanna
OOF R² = 0.135
OOF RMSE = 0.598
N = 20,927
Forest-Grass
OOF R² = 0.266
OOF RMSE = 0.711
N = 684
Shrub-Grass
OOF R² = 0.433
OOF RMSE = 0.807
N = 64
Savanna-Grass
OOF R² = 0.287
OOF RMSE = 0.553
N = 1,320
Forest-Crop
OOF R² = 0.310
OOF RMSE = 0.440
N = 4,825
Shrub-Crop
OOF R² = 0.453
OOF RMSE = 0.317
N = 2,564
Savanna-Crop
OOF R² = 0.204
OOF RMSE = 0.388
N = 4,124
Grass-Crop
OOF R² = 0.332
OOF RMSE = 0.665
N = 13,616
Shrub-Urban
OOF R² = 0.221
OOF RMSE = 0.646
N = 74
Savanna-Urban
OOF R² = 0.150
OOF RMSE = 0.439
N = 141
Grass-Urban
OOF R² = 0.327
OOF RMSE = 0.609
N = 422
Crop-Urban
OOF R² = 0.154
OOF RMSE = 0.567
N = 42,243
Shrub-Barren
OOF R² = 0.135
OOF RMSE = 0.564
N = 53
Grass-Barren
OOF R² = 0.351
OOF RMSE = 1.316
N = 650
Crop-Barren
OOF R² = 0.347
OOF RMSE = 0.590
N = 102
Urban-Barren
OOF R² = 0.609
OOF RMSE = 0.413
N = 106
OOF predicted ΔLST
Observed ΔLST


XGBoost | Response: ΔLST Day
Forest–Savanna
OOF R² = 0.350
OOF RMSE = 0.719
N = 20,927
Forest–Grass
OOF R² = 0.480
OOF RMSE = 1.109
N = 684
Shrub–Grass
OOF R² = 0.829
OOF RMSE = 0.619
N = 64
Savanna–Grass
OOF R² = 0.367
OOF RMSE = 0.916
N = 1,320
Forest–Crop
OOF R² = 0.474
OOF RMSE = 0.688
N = 4,825
Shrub–Crop
OOF R² = 0.634
OOF RMSE = 0.778
N = 2,564
Savanna–Crop
OOF R² = 0.618
OOF RMSE = 0.656
N = 4,124
Grass–Crop
OOF R² = 0.459
OOF RMSE = 1.141
N = 13,616
Shrub–Urban
OOF R² = 0.495
OOF RMSE = 0.627
N = 74
Savanna–Urban
OOF R² = 0.092
OOF RMSE = 1.131
N = 141
Grass–Urban
OOF R² = 0.574
OOF RMSE = 1.196
N = 422
Crop–Urban
OOF R² = 0.325
OOF RMSE = 0.907
N = 42,243
Shrub–Barren
OOF R² = -0.114
OOF RMSE = 1.034
N = 53
Grass–Barren
OOF R² = 0.535
OOF RMSE = 2.291
N = 650
Crop–Barren
OOF R² = 0.369
OOF RMSE = 0.983
N = 102
Urban–Barren
OOF R² = 0.772
OOF RMSE = 0.690
N = 106
OOF predicted ΔLST
Observed ΔLST

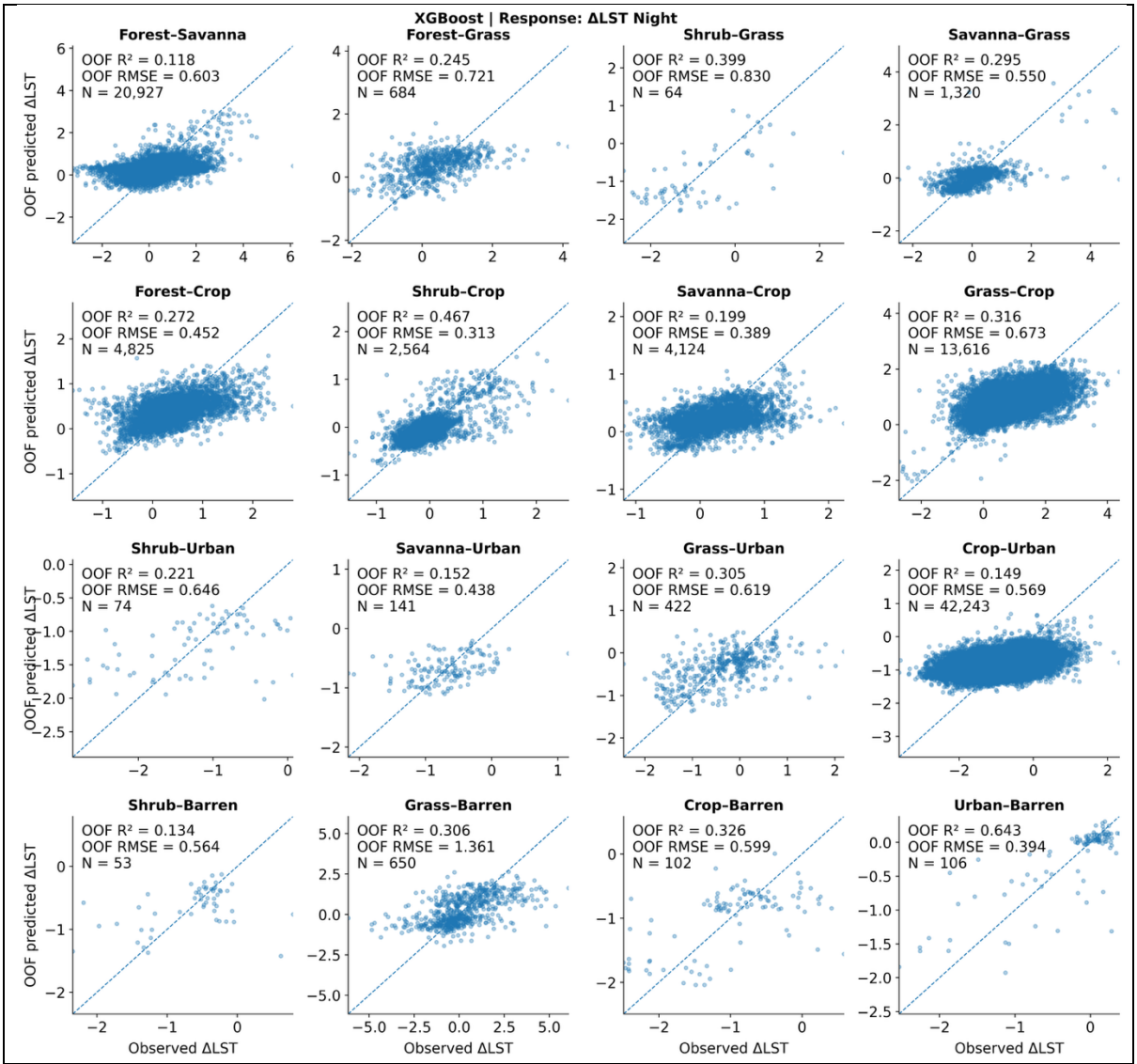


Fig. S8. Out-of-fold predictive performance of machine-learning models for land surface temperature differences (ΔLST) across land-cover transitions. Scatterplots compare observed and out-of-fold (OOF) predicted ΔLST for Random Forest and XGBoost models under daytime and nighttime conditions. Each panel represents an individual land-cover transition and reports the OOF coefficient of determination (R^2), root-mean-square error (RMSE), and sample size (N). The diagonal 1:1 line represents perfect agreement between observed and predicted ΔLST; departures from this line indicate prediction errors.