Regime-dependent reversal in temporal asymmetry of ecosystem carbon exchange across global biomes

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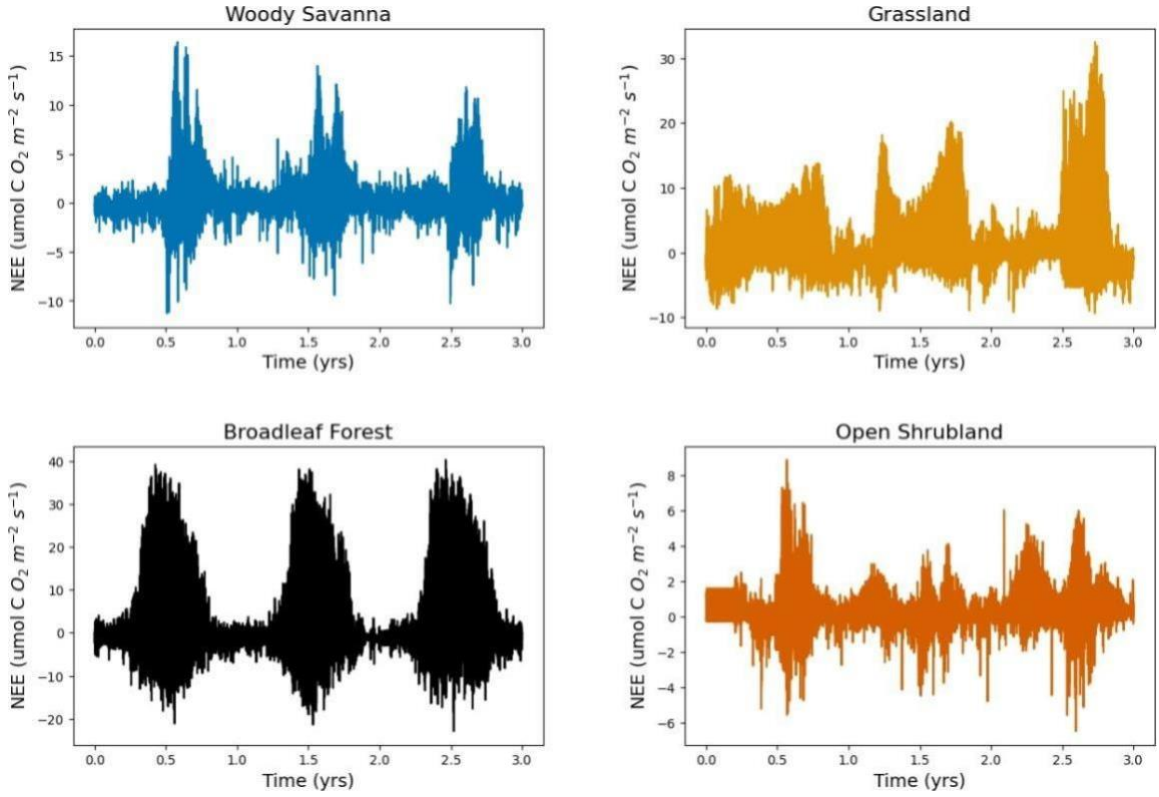
Supplementary information

This supplementary information document consists of additional tables and figures that support the main findings of our manuscript. The document provides details of site characteristics of all the 13 study sites in Table S1, description of the FLUXNET variables used in our study Table S2, details of the key variables used in the NEP asymmetry analysis in Table S3, a step-by-step methodology of NEP asymmetry calculation is described in Table S4, a quality control analysis assessing the proportion of gap-filled data within the identified extreme events in Table S5, and Table S6 and S7 summarize the best fit relationships for all variables and the statistical metrics for all fits for all fluctuations and extreme fluctuations respectively. It also includes illustrations of Net Ecosystem Productivity (NEP) time series (Figure S1), site-specific fluctuation paths and asymmetry coefficients (Figures S2–S5), the robustness of the asymmetry metric to varying extreme thresholds (Figures S6), and the relationships between asymmetry and potential environmental drivers across different ecosystems (Figures S7-S17).

1. Examples of NEP Time-Series

Figure S1: Single panels showing the timeseries of Broadleaf Forest, Woody Savanna, Open Shrubland, and Grassland



2. *Analysis of Fluctuation Paths*

Figure S2: Top 1% fluctuation paths (light gray) and their average (thick dark gray) for all sites

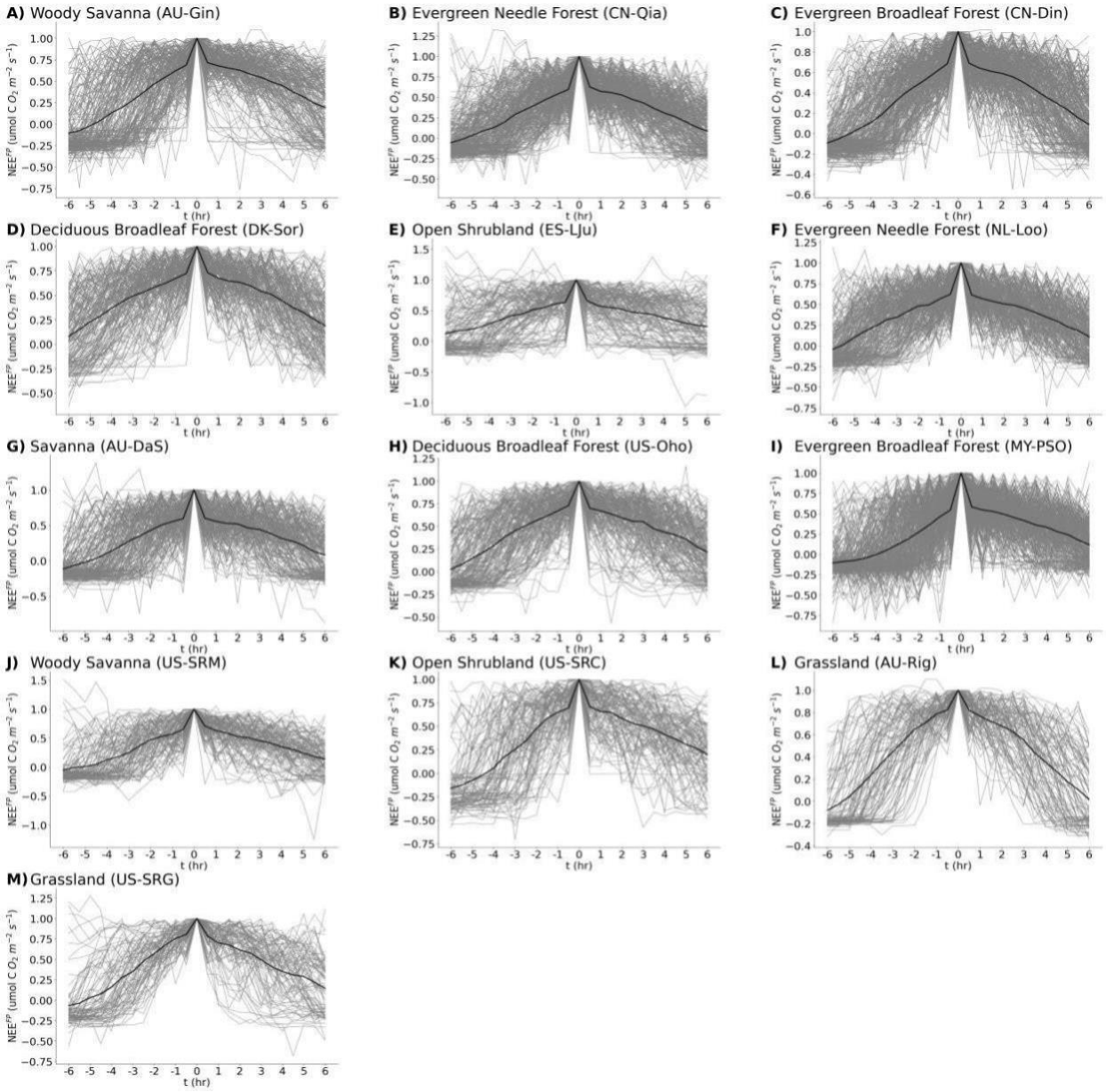
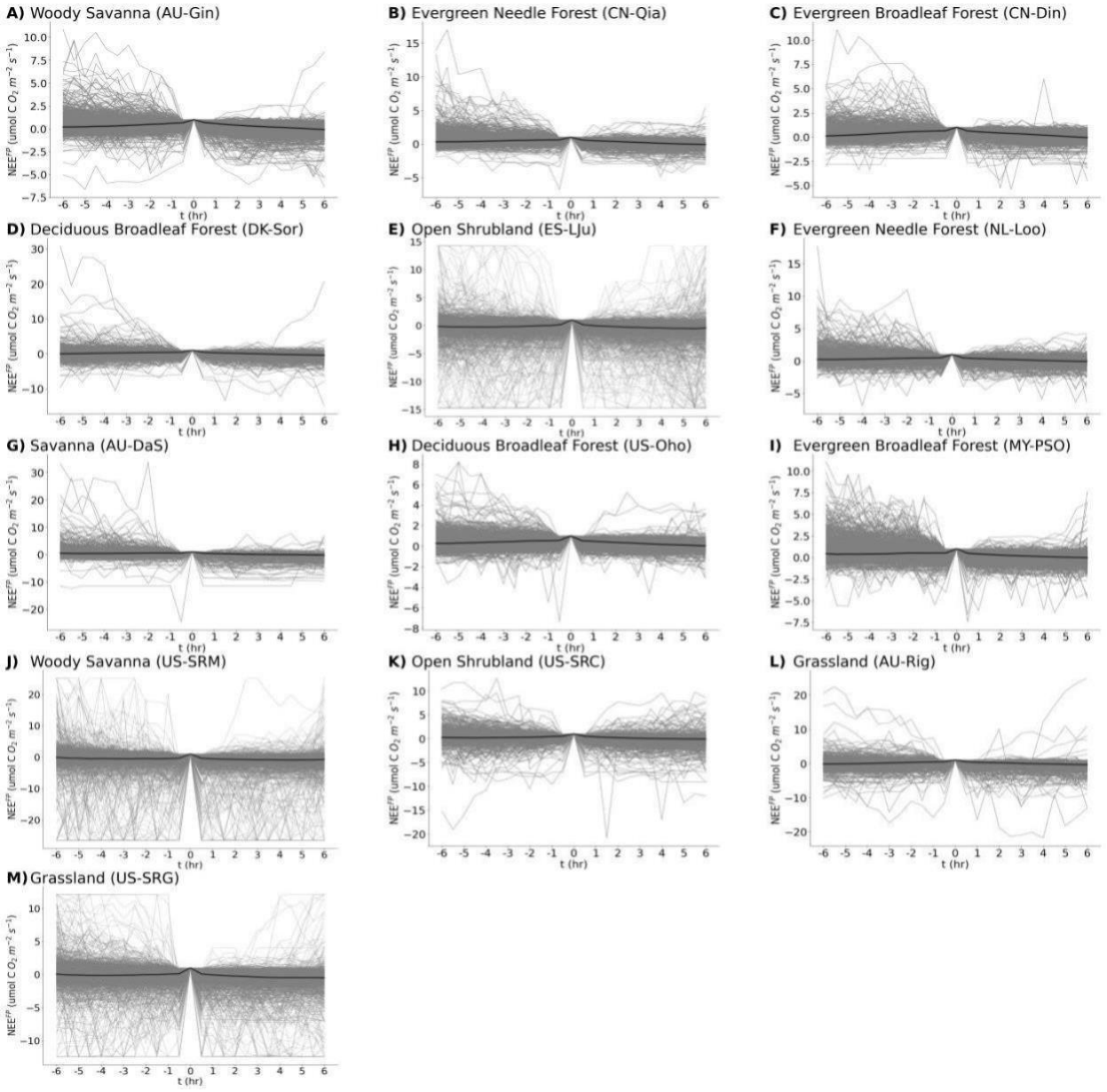


Figure S3: Fluctuation paths (light gray) and their average (thick dark gray) for all fluctuations (c=0) for all sites



3. *Analysis of Asymmetry Coefficient*

Figure S4: Asymmetry Coefficients (light gray) and their average (thick dark gray) for top 1% fluctuations for all sites

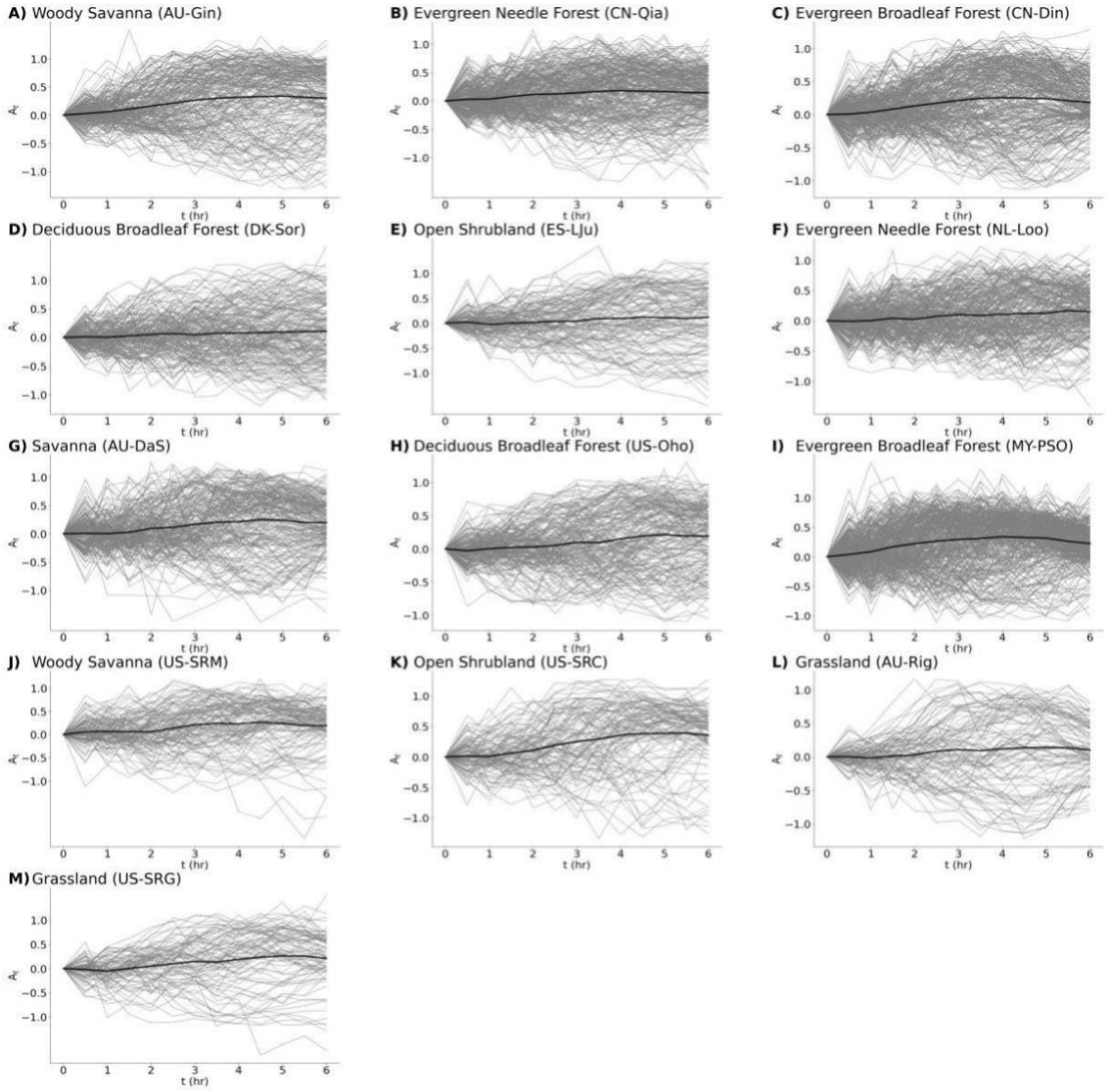
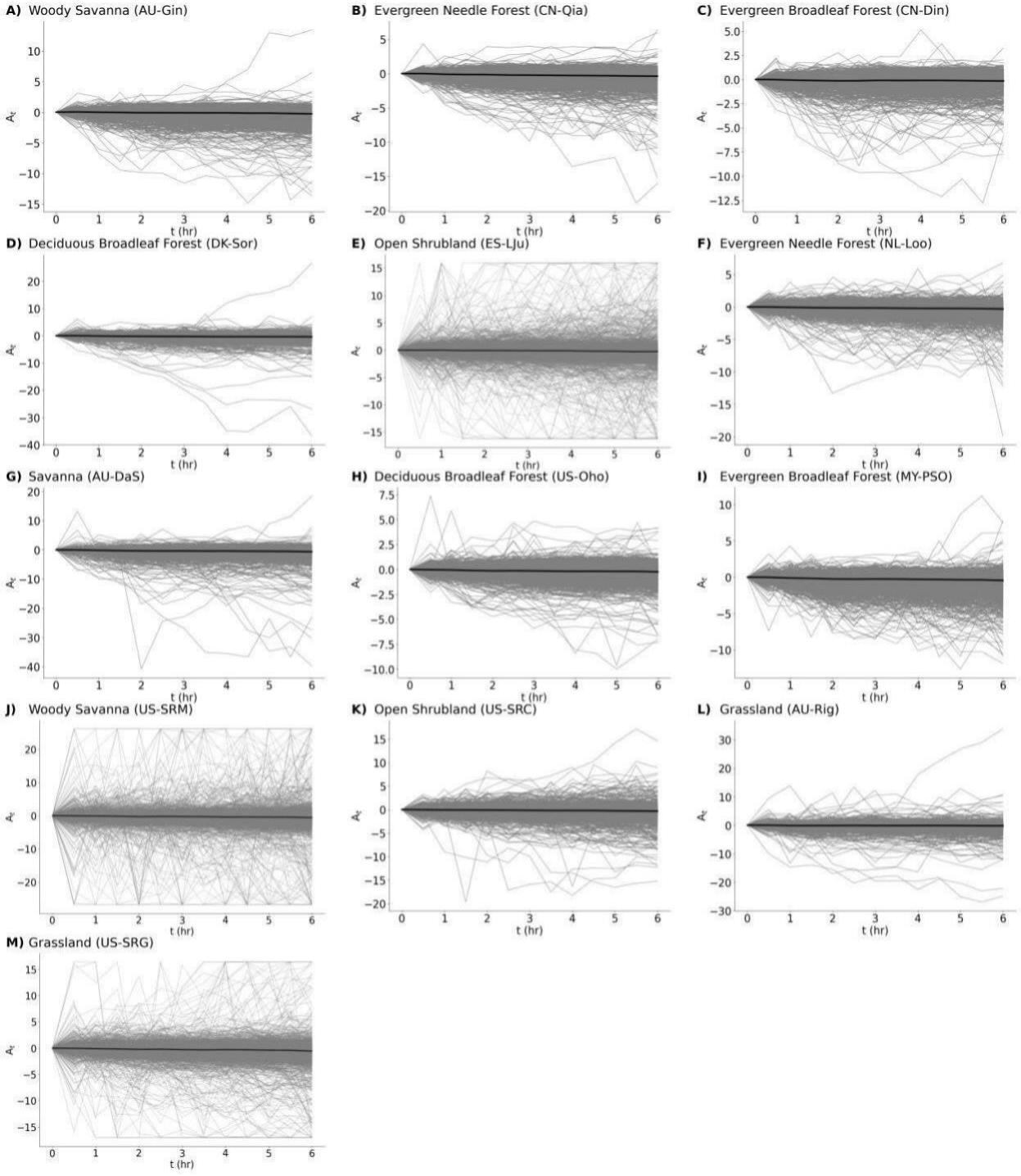
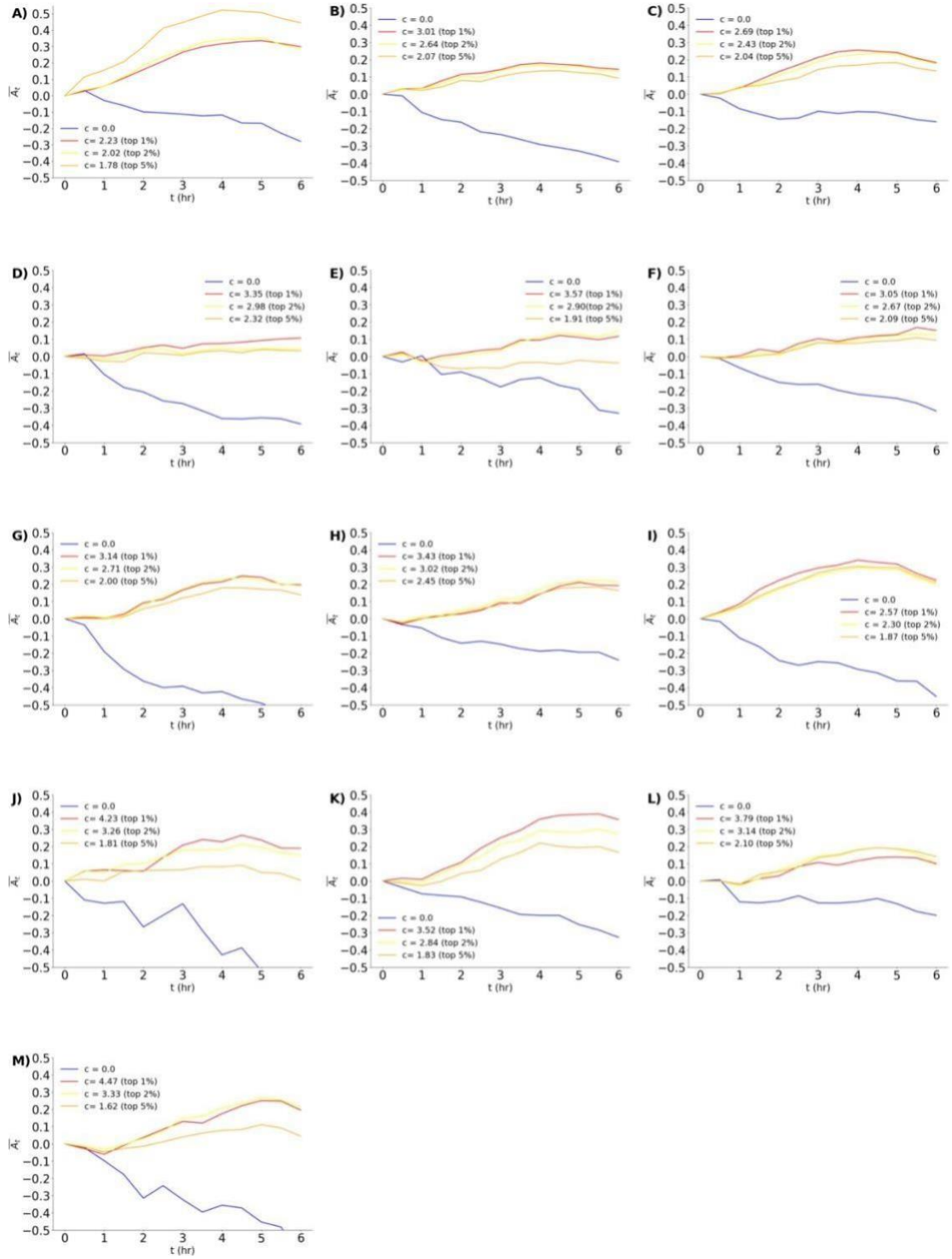


Figure S5: Asymmetry Coefficients (light gray) and their average (thick dark gray) for all fluctuations (c=0) for all sites



4. Sensitivity of Asymmetry to Threshold Selection

Figure S6: Sensitivity of the average asymmetry coefficient across all 13 sites evaluated at three extreme fluctuation thresholds: top 1% (99th quantile), top 2% (98th quantile), and top 5% (95th quantile)



5. *Analysis of potential drivers of asymmetry for top 1% fluctuations (extremes)*

Figure S7: Relationship between average NEP asymmetry and 3yr shortwave radiation average, and daily average shortwave radiation for top 1% fluctuations for all sites

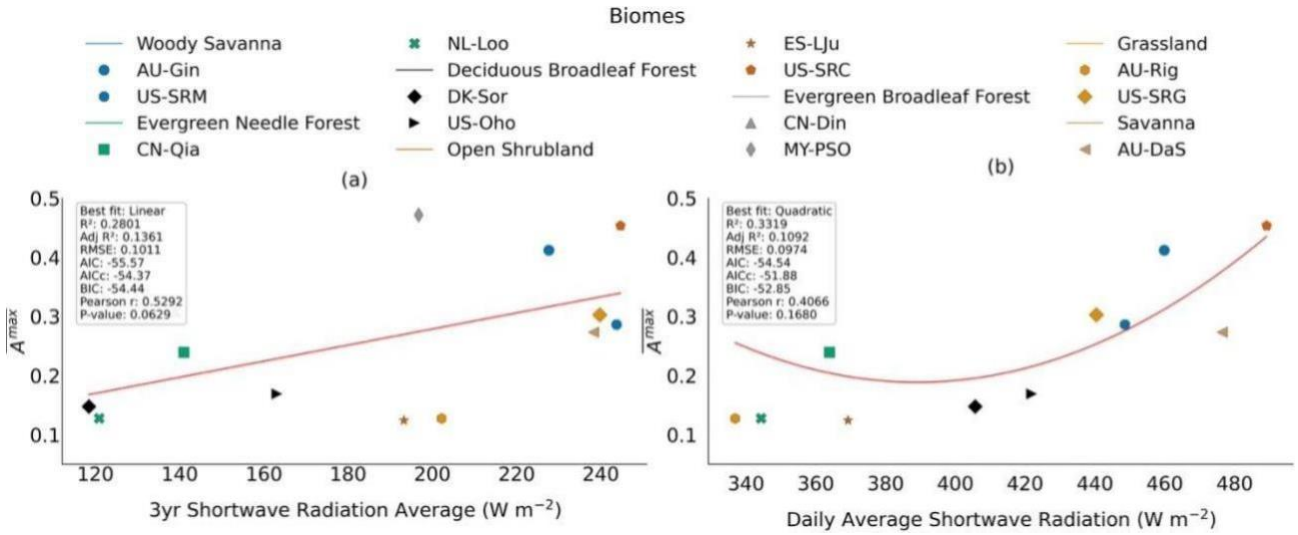


Figure S8: Relationship between average NEP asymmetry and 3yr soil moisture average, and daily average soil moisture for top 1% fluctuations for all sites

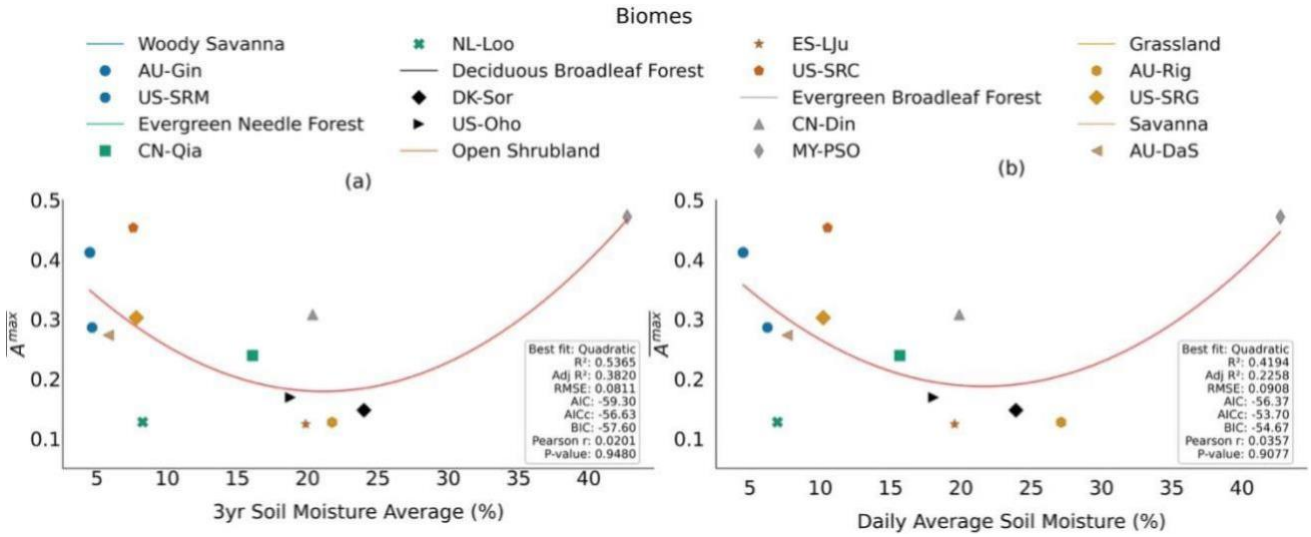


Figure S9: Relationship between average NEP asymmetry and 3yr precipitation average, and daily average precipitation for top 1% fluctuations for all sites

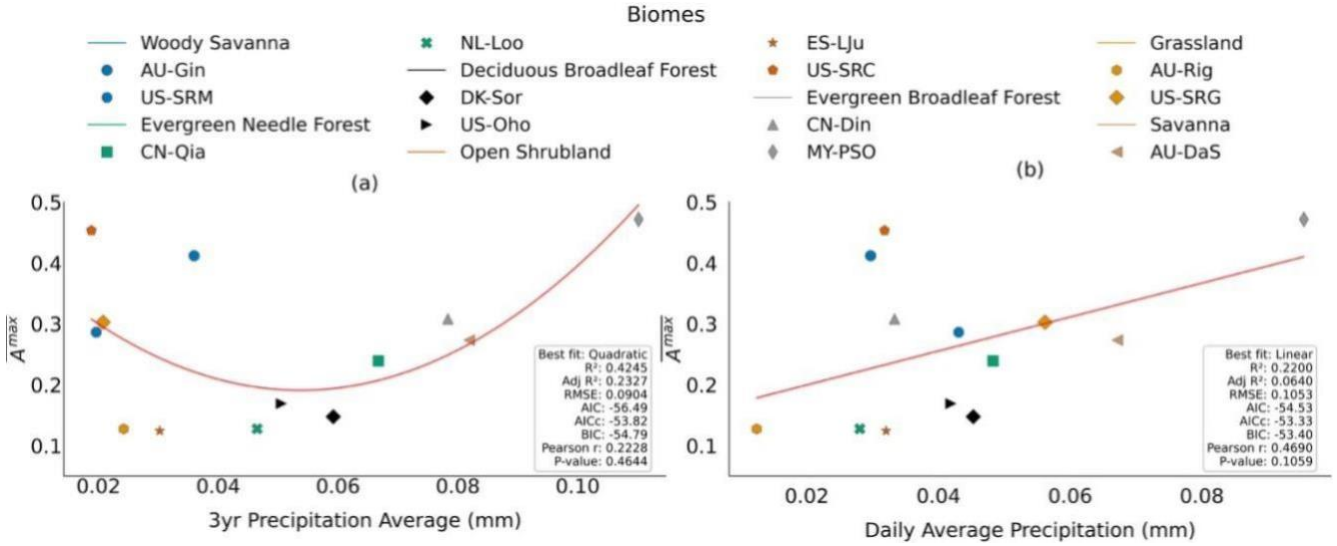


Figure S10: Relationship between average NEP asymmetry and 3yr vapor pressure deficit average, and daily average vapor pressure deficit for top 1% fluctuations for all sites

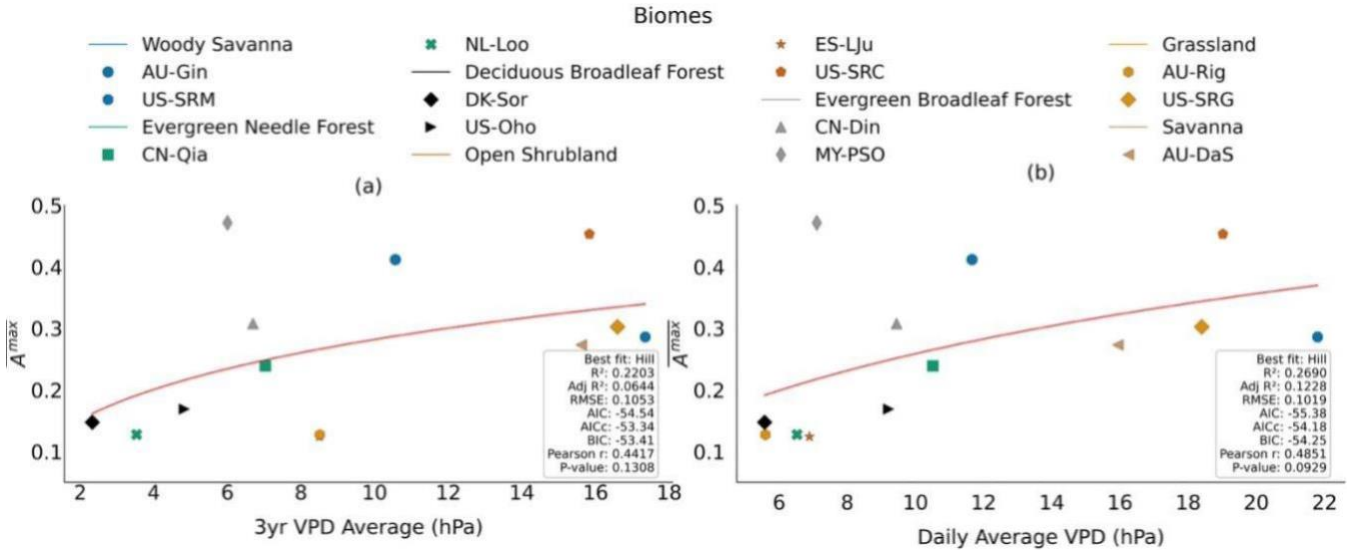
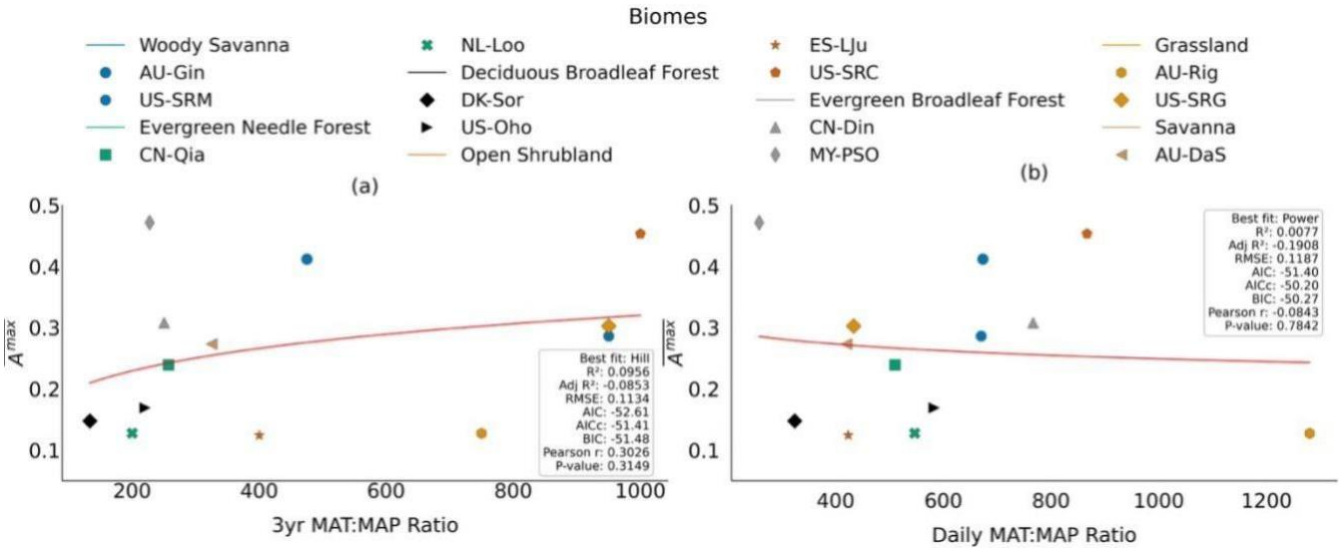


Figure S11: Relationship between average NEP asymmetry and 3yr Mean Annual Temperature: 3yr Mean Annual Precipitation and daily Mean Annual Temperature: daily Mean Annual Precipitation for top 1% fluctuations for all sites



6. *Analysis of potential drivers of asymmetry for all fluctuations*

Figure S12: Relationship between average NEP asymmetry and 3yr temperature average for all fluctuations for all sites

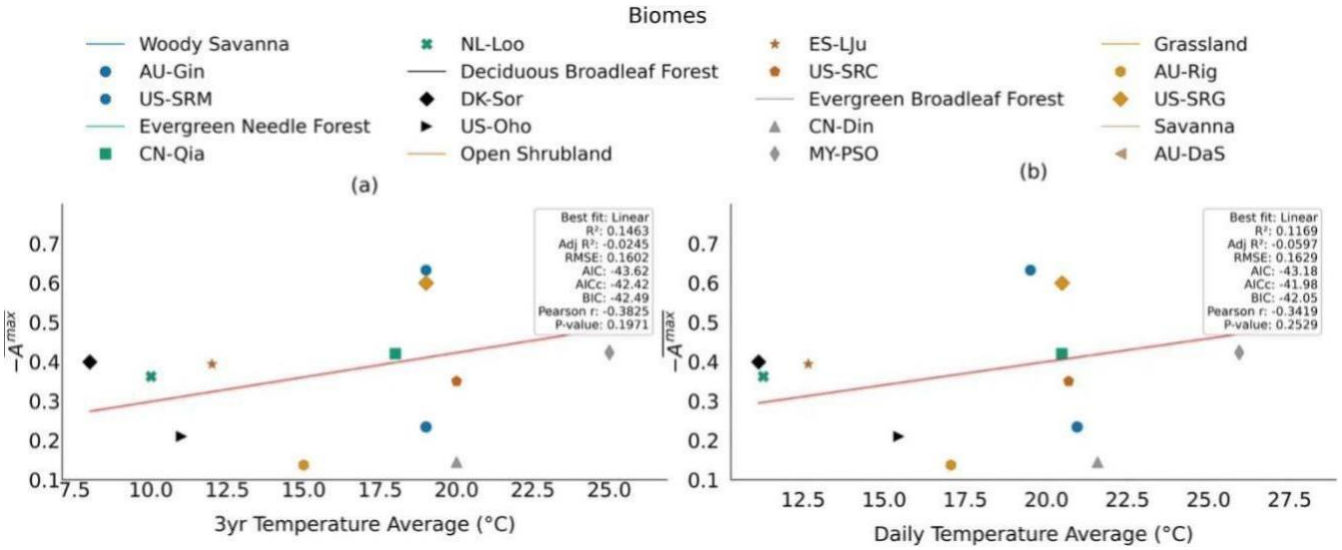


Figure S13: Relationship between average NEP asymmetry and 3yr shortwave radiation average, and daily average shortwave radiation for all fluctuations for all sites

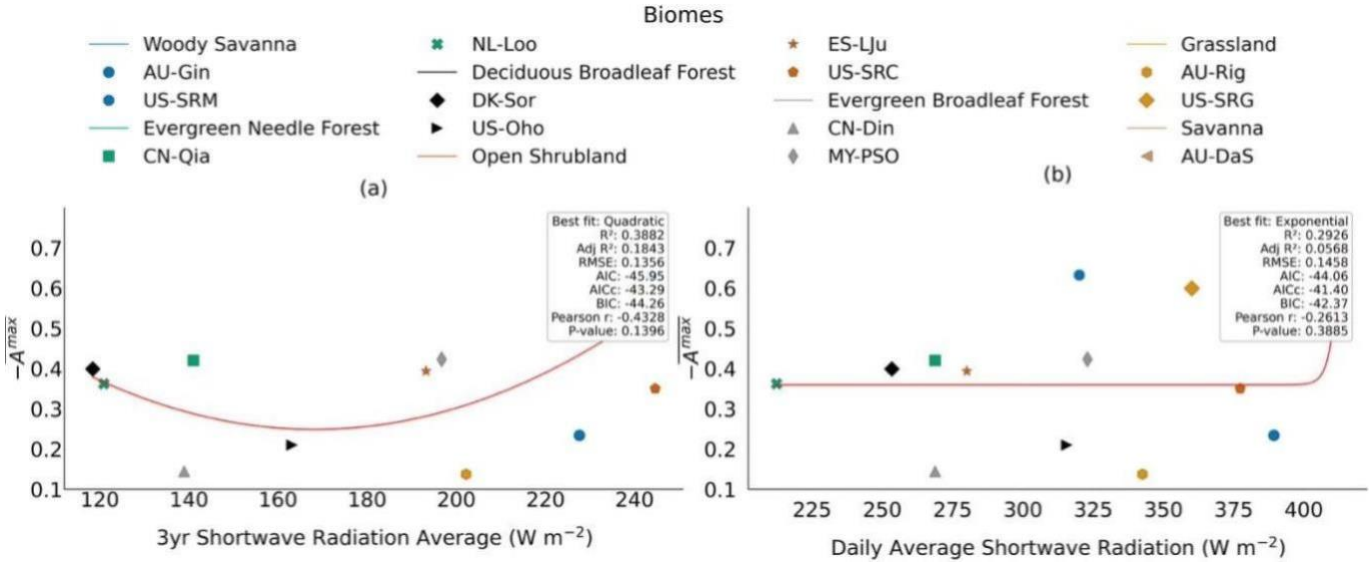


Figure S14: Relationship between average NEP asymmetry and 3yr soil moisture average, and daily average soil moisture for all fluctuations for all sites

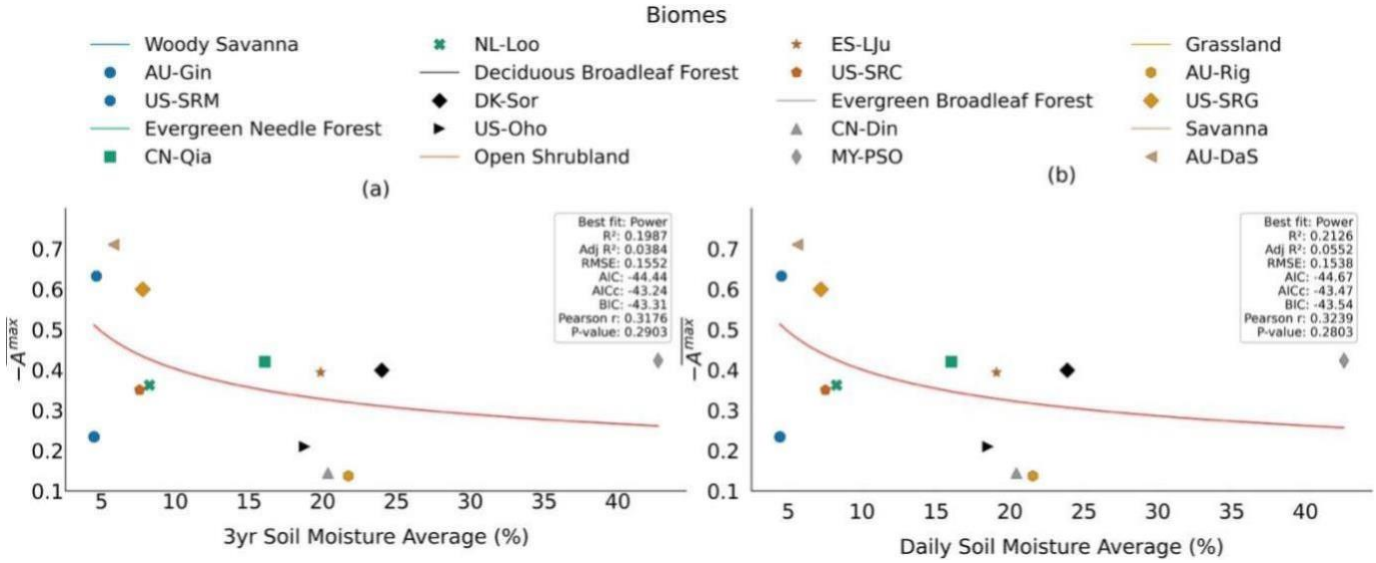


Figure S15: Relationship between average NEP asymmetry and 3yr precipitation average, and daily average precipitation for all fluctuations for all sites

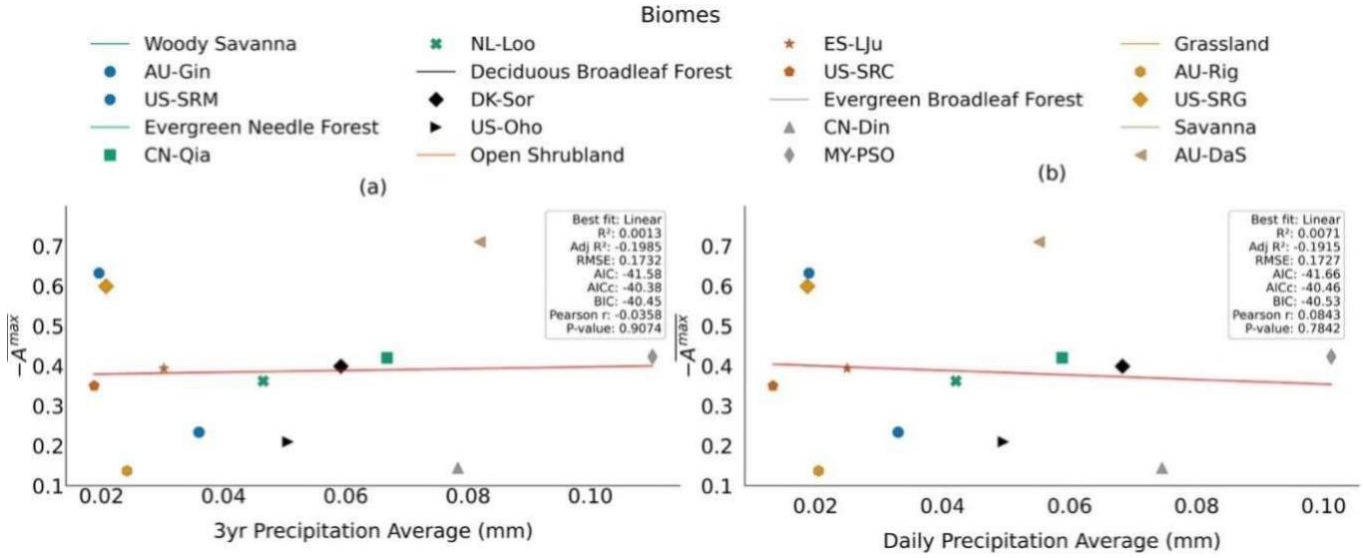


Figure S16: Relationship between average NEP asymmetry and 3yr Mean Annual Temperature: 3yr Mean Annual Precipitation and daily Mean Annual Temperature: daily Mean Annual Precipitation for all fluctuations for all sites

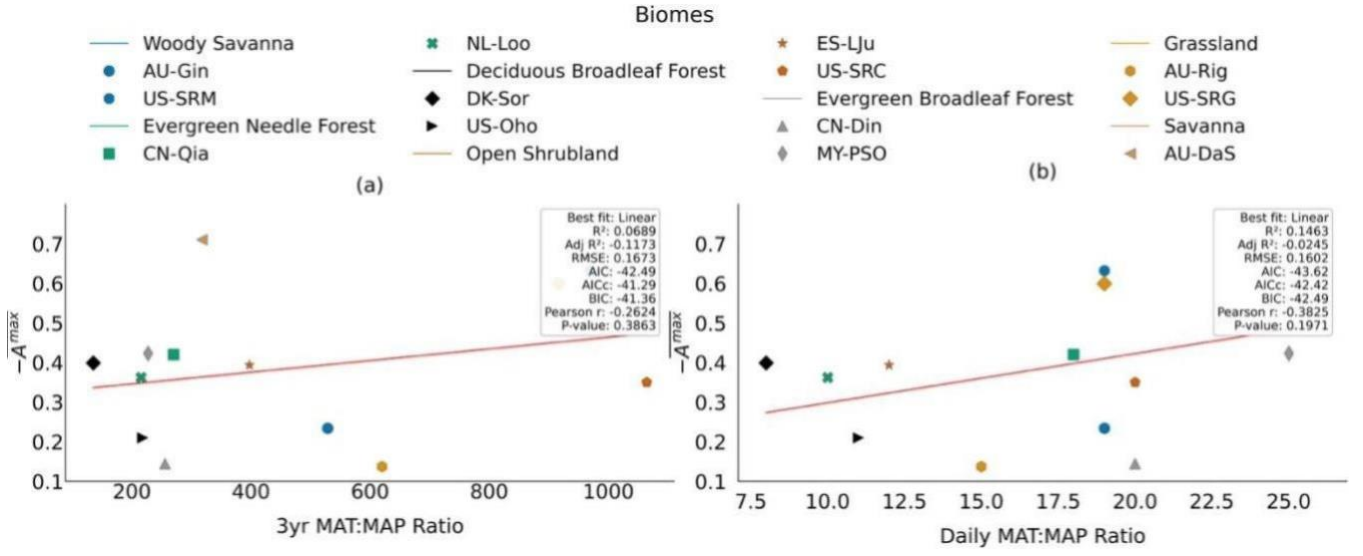
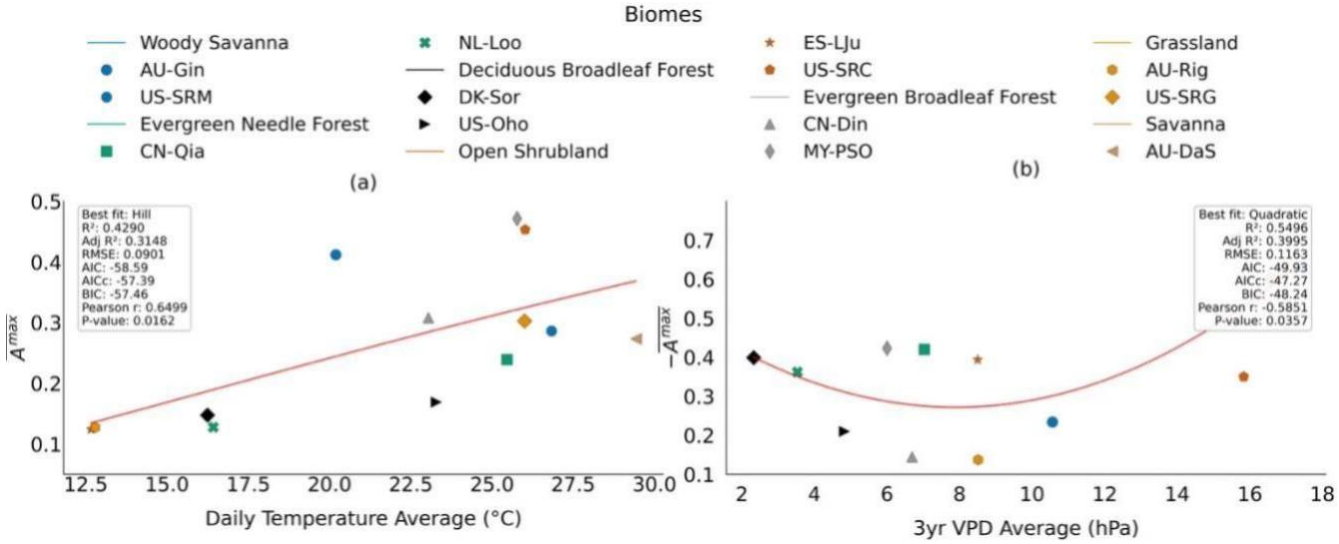


Figure S17: Relationship between average NEP asymmetry and daily average temperature for top 1% fluctuations for all sites and 3yr vapor pressure deficit average for all fluctuations for all sites



1. Description of selected sites

Table S1: Overview of thirteen sites key characteristics

SITE	LATITUDE (°)	LONGITUDE (°)	IGBP (International Geosphere–Biosphere Programme)	LONG TERM MEAN ANNUAL TEMP (°C)	MEAN ANNUAL TEMP FOR STUDIED PERIOD (°C)	LONG TERM MEAN ANNUAL PRECIP. (mm)	STUDIED TIME PERIOD (years)	MEAN NEP FOR STUDIED PERIOD ($\mu molCO_2 m^{-2} s^{-1}$)
AU-Gin	-31.3764	115.7138	WSA (Woody Savannas)	19.21	19	641	2011-2013	-0.614
AU-DaS	-14.1593	131.3881	SAV (Savannas)	27.22	26.35	975.82	2011-2013	0.502
CN-Din	23.1733	112.5361	EBF (Evergreen Broadleaf Forests)	19.64	20.43	1618.1	2003-2005	1.378
CN-Qia	26.7414	115.0581	ENF (Evergreen Needleleaf Forests)	18.95	18	1466.75	2003-2005	1.511
DK-Sor	55.4859	11.6446	DBF (Deciduous Broadleaf Forests)	8.2	8	660	2009-2011	0.742
ES-LJu	36.9266	-2.7521	OSH (Open Shrublands)	16	12	400	2011-2013	0.032
US-Oho	41.5545	-83.8438	DBF (Deciduous Broadleaf Forests)	10.1	11.10	849	2011-2013	2.151
NL-Loo	52.1666	5.7436	ENF (Evergreen Needleleaf Forests)	9.8	10	786	2003-2005	1.367
MY-PSO	2.9730	102.3062	EBF (Evergreen Broadleaf Forests)	25.34	25.07	1804	2007-2009	2.548
US-SRM	31.8214	-110.8661	WSA (Woody Savannas)	17.92	18.90	380	2011-2013	0.010
US-SRC	31.9083	-110.8395	OSH (Open Shrublands)	22	19.62	330	2008-2010	0.138
AU-Rig	-36.6499	145.5759	GRA (Grasslands)	15.57	15.41	650	2011-2013	0.326
US-SRG	31.7894	-110.8277	GRA (Grasslands)	17	18.67	420	2012-2014	0.080

Table S2: Overview of FLUXNET variables used in this study

VARIABLE	FLUXNET CODE	DESCRIPTION
Net Ecosystem Exchange	NEE_VUT_REF	Net CO_2 exchange derived using Variable USTAR Threshold method
Air Temperature	TA_F	Air temperature consolidated from TA_F_MDS and TA_ERA
Incoming Shortwave Radiation	SW_IN_F	Shortwave radiation consolidated from SW_IN_F_MDS and SW_IN_ERA (negative values set to zero)
Vapor Pressure Deficit	VPD_F	Vapor Pressure Deficit consolidated from VPD_F_MDS and VPD_ERA
Precipitation	P_F	Precipitation consolidated from P and P_ERA
Soil Water Content	SWC_F_MDS_1	Gap-filled soil water content using MDS method
Ecosystem Respiration (nighttime)	RECO_NT_VUT_REF	Ecosystem respiration from nighttime partitioning method using VUT filtering
Ecosystem Respiration (daytime)	RECO_DT_VUT_REF	Ecosystem respiration from daytime partitioning method using VUT filtering
Gross Primary Production (nighttime)	GPP_NT_VUT_REF	GPP from nighttime partitioning method using VUT filtering
Gross Primary Production (daytime)	GPP_DT_VUT_REF	GPP from daytime partitioning method using VUT filtering
Timestamp	TIMESTAMP_END	ISO timestamp end of averaging period (YYYYMMDDHHMM format)

2. Description of key variables and calculations for NEP Asymmetry Analysis

Table S3: Overview of key variables for NEP asymmetry analysis

SYMBOL	VARIABLE DEFINITION
NEP	Net Ecosystem Productivity (NEP), i.e., the negative of Net Ecosystem Exchange (NEE).
NEP^{max}	The maximum NEP value (peak value) for a large fluctuation.
t_p	Time at which the peak NEP value, NEP^{max}, occurs.
NEP^{FP}_{t}	Falling limb of the fluctuation path: Portion of NEP starting at peak time and continuing for 6 hours after the peak, representing how NEP decreases as the system returns towards its equilibrium.
NEP^{FP}_{-t}	Rising limb of the fluctuation path: Portion of NEP starting 6 hours before the peak and ending at peak time, showing how NEP increases as it approaches NEP^{max}.
A_t	Asymmetry coefficient at time t, measuring the difference between falling and rising limbs.
$\mathbf{A_t}$	The average asymmetry coefficient across all fluctuation paths.
$\overline{A^{max}}$	Maximum value of asymmetry coefficient which is the peak value A_t across time t.
τ	Half-width of the time window around tp, defining the length of the fluctuation path.
σ	Standard deviation of NEP over the considered 3 yr period.
c	Coefficient that is used to calculate and set the threshold for identifying fluctuations, with a chosen quantile percentage (e.g., top 1% fluctuations).
μ	Mean of NEP over the considered 3 yr period.

Table S4: Overview of steps and formulas for NEP asymmetry analysis

STEP	FORMULA
1. Threshold Calculation	
1.1 Set the threshold to identify large fluctuations.	$NEP^{threshold} = \mu + c\sigma$
2. Fluctuation Path Identification	
2.1 Identify the peak of each fluctuation that exceeds the threshold, and mark the peak time t_p.	$NEP^{max} = \max(NEP)$
2.2 Define the fluctuation path around each peak with a time window of width 2τ centered around t_p.	$[t_p - \tau, t_p + \tau]$, where $\tau = 6$ hrs
2.3 Normalize each fluctuation path by its peak NEP value.	$NEP^{FP}_t = NEP_t / NEP^{max}$
3. Asymmetry Coefficient Calculation	
3.1 Calculate the difference between falling and rising limbs.	$A_t = NEP^{FP}_t - NEP^{FP}_{-t}$
3.2 Calculate the average asymmetry across all fluctuation paths to quantify time asymmetry.	$A_t = 1/N \sum_{i=1}^{N} A^i_t$
4. Peak Asymmetry Calculation	
4.1 Calculate the maximum value of asymmetry coefficient for each fluctuation path.	$\overline{A^{max}} = \max(A_t)$

3. Details of quality control analysis of top 1% extreme fluctuations across all sites

Table S5: Overview of the total number of identified extremes per site, with the count and percentage of those extremes (top1% peaks) that correspond to gap-filled data (NEE_VUT_REF_QC > 0).

SITE	TOTAL EXTREMES	GAP-FILLED EXTREMES	PERCENT GAP-FILLED (%)	SHARE OF TOTAL GAP-FILLED DATA (%)
AU-DaS	211	27	12.80	8.5
AU-Gin	212	14	6.60	4.4
AU-Rig	99	40	40.40	12.5
CN-Din	298	49	16.44	15.4
CN-Qia	274	13	4.74	4.1
DK-Sor	189	7	3.70	2.2
ES-LJu	131	3	2.29	0.9
MY-PSO	378	10	2.65	3.1
NL-Loo	262	51	19.47	16.0
US-Oho	194	39	20.10	12.2
US-SRC	114	23	20.18	7.2
US-SRG	85	5	5.88	1.66
US-SRM	124	38	30.65	11.9
TOTAL	**2571**	**319**	**12.41**	**100.0**

4. Details of statistical metrics for best fit model selection for all environmental drivers

Table S6: Overview of best fit relationships for all variables for top 1% fluctuations

ENVIRONMENTAL DRIVER	R^2	ADJUSTED R^2	ROOT MEAN SQUARED ERROR (RMSE)	AKAIKE INFORMATION CRITERION (AIC)	CORRECTED AIC (AICc)	BAYESIAN INFORMATION CRTIERION (BIC)	PEARSON CORRELATION COEFFICIENT (r)	P-Value	BEST FIT
3yr Temperature	0.5908	0.5089	0.0762	-62.92	-61.72	-61.79	0.7535	0.0029	Hill
3yr Shortwave Radiation	0.2801	0.1361	0.1011	-55.57	-54.37	-54.44	0.5292	0.0629	Linear
3yr Precipitation	0.4245	0.2327	0.0904	-56.49	-53.82	-54.79	0.2228	0.4644	Quadratic
3yr Soil Moisture	0.5365	0.3280	0.0811	-59.30	-56.63	-57.60	0.0201	0.9480	Quadratic
3yr Vapor Pressure Deficit	0.2203	0.0644	0.1053	-54.54	-53.34	-53.41	0.4417	0.1308	Hill
3yr MAT: 3yr MAP	0.0956	-0.0853	0.1134	-52.61	-51.41	-51.48	0.3026	0.3149	Hill
Daily Temperature	0.4484	0.3380	0.0885	-59.03	-57.83	-57.90	0.6499	0.0162	Hill
Daily Shortwave Radiation	0.3319	0.1092	0.0974	-54.54	-51.88	-52.85	0.4066	0.1680	Quadratic
Daily Precipitation	0.2200	0.0640	0.1053	-54.53	-53.33	-53.40	0.4690	0.1059	Linear
Daily Soil Moisture	0.4194	0.2258	0.0908	-56.37	-53.70	-54.67	0.0357	0.9077	Quadratic
Daily Vapor Pressure Deficit	0.2690	0.1228	0.1019	-55.38	-54.18	-54.25	0.4851	0.0929	Hill
Daily MAT: Daily MAP	0.5873	0.3809	0.0766	-58.81	-53.81	-56.55	-0.0843	0.7842	Cubic

Table S7: Overview of best fit relationships for all variables for all fluctuations

ENVIRONMENTAL DRIVER	R^2	ADJUSTED R^2	ROOT MEAN SQUARED ERROR (RMSE)	AKAIKE INFORMATION CRITERION (AIC)	CORRECTED AIC (AICc)	BAYESIAN INFORMATION CRTIERION (BIC)	PEARSON CORRELATION COEFFICIENT (r)	P-Value	BEST FIT
3yr Temperature	0.1463	-0.0245	0.1602	-43.62	-42.42	-42.49	-0.3825	0.1971	Linear
3yr Shortwave Radiation	0.3382	0.1843	0.1356	-45.95	-43.29	-44.26	-0.4328	0.1396	Quadratic
3yr Precipitation	0.0013	-0.1985	0.1732	-41.58	-40.38	-40.45	-0.0358	0.9074	Linear
3yr Soil Moisture	0.1987	0.0384	0.1552	-44.44	-43.24	-43.31	0.3176	0.2903	Power
3yr Vapor Pressure Deficit	0.5496	0.3995	0.1163	-49.93	-47.27	-48.24	-0.5851	0.0357	Quadratic
3yr MAT: 3yr MAP	0.0689	-0.1173	0.1673	-42.49	-41.29	-41.36	-0.2624	0.3863	Linear
Daily Temperature	0.1169	-0.0597	0.1629	-43.18	-41.98	-42.05	-0.3419	0.2529	Linear
Daily Shortwave Radiation	0.2926	0.0568	0.1458	-44.06	-41.40	-42.37	-0.2613	0.3885	Exponential
Daily Precipitation	0.0071	-0.1915	0.1727	-41.66	-40.46	-40.53	0.0843	0.7842	Linear
Daily Soil Moisture	0.2126	0.0552	0.1538	-44.67	-43.47	-43.54	0.3239	0.2803	Power
Daily Vapor Pressure Deficit	0.6352	0.5136	0.1047	-52.68	-50.01	-50.98	-0.5880	0.0345	Quadratic
Daily MAT: Daily MAP	0.0501	-0.1399	0.1689	-42.23	-41.03	-41.10	-0.2111	0.4888	Power