

Supplementary Materials for
Atmospheric aridity drives functional reorganisation and
resilience loss in global forests

This file includes:
Supplementary Notes
Figs. S1 to S6
Tables S1 to S4

SUPPLEMENTARY NOTES

Supplementary note 1: Binning analysis to separate VPD and SM effects

To separate the individual effects of VPD and SM on coupling strength, we performed a binning analysis in which forest pixels were stratified into deciles based on either SM or VPD. Within each decile, we calculated Spearman correlations between coupling strength and the non-stratified climate variable. We also computed the residual correlation between VPD and SM within each decile. Only deciles in which the residual correlation was weak ($|r| < 0.15$) were retained for interpretation, ensuring adequate separation of the two drivers (Supplementary Table S1).

Supplementary note 2: Sensitivity analysis using GLDAS Noah soil moisture

Our primary analysis used soil moisture from TerraClimate, which derives SM from a modified Thornthwaite-Mather water balance model with static reference land cover. To evaluate whether this data source affects our conclusions, we conducted a sensitivity analysis using root-zone soil moisture from the GLDAS Noah Land Surface Model v2.1 (0.25° resolution). GLDAS Noah incorporates energy balance processes, multi-layer soil physics, and satellite-derived vegetation phenology, providing an independent test of our findings.

We tested four depth configurations to capture potential depth-dependent effects: 0–10 cm (surface layer), 0–40 cm (shallow root zone), 0–100 cm (intermediate root zone), and 0–200 cm (full root zone). SEM models were fitted separately for each climate zone (Tropical, Arid, Temperate, Boreal) and forest type (Intact, Non-intact), following the same procedures as in the primary analysis.

VPD to AR(1) pathway: VPD consistently showed positive and significant effects on AR(1) across most climate zones and forest types, with path coefficients ranging from +0.18 to +0.53. Non-intact forests exhibited consistently higher sensitivity (+0.47 to +0.53) compared to intact forests (+0.20 to +0.21), confirming the amplified

vulnerability identified in the primary analysis.

SM to AR(1) pathway: SM showed negative effects on AR(1) in Tropical, Arid, and Temperate zones (coefficients: -0.12 to -0.39 , $P < 0.05$), confirming its mitigating role. This effect was weak or non-significant in Boreal forests, consistent with lower water limitation in energy-limited high-latitude systems.

Resilience-mediated pathway: The AR(1) to GPP-WUE coupling path remained positive and significant in Tropical forests across all depth configurations (coefficients: $+0.25$ to $+0.28$, $P < 0.05$), supporting the resilience-mediated pathway identified in the primary analysis. In Boreal forests, this path was weaker but remained significant in most configurations.

Intact vs. Non-intact contrast: The contrasting response patterns were replicated. In intact forests, VPD exerted strong direct negative effects on GPP-WUE coupling (-0.58 to -0.66), whereas in non-intact forests, VPD effects were channeled primarily through resilience loss. The AR(1) to GPP-WUE path in intact forests reversed sign from -0.06 ($P < 0.05$) in the primary analysis (TerraClimate SM) to $+0.068$ to $+0.074$ ($P < 0.01$) in the GLDAS sensitivity analysis, likely reflecting variance redistribution between direct and indirect pathways under different SM characterizations. This does not affect the primary interpretation, as the dominant direct VPD to GPP-WUE effect (-0.58 to -0.66 , $P < 0.01$) remains fully consistent across all configurations.

These results demonstrate that our core conclusions are robust to both the choice of SM product and the definition of root-zone depth.

Supplementary note 3: Sensitivity analysis with deseasonalized coupling metrics

The core finding, that VPD drives resilience loss, was fully replicated across all climate zones with sufficient sample sizes (Tropical: VPD to AR(1) = $+0.37$, $P < 0.01$; Temperate: $+0.30$, $P < 0.01$; Boreal: $+0.20$, $P < 0.01$). The resilience-mediated pathway was preserved and in Temperate forests strengthened relative to the primary analysis (AR(1) to GPP-WUE coupling: $+0.37$ vs. $+0.02$ in the primary analysis).

One notable divergence is that the AR(1) to GPP-EPE path in Boreal forests reversed sign from -0.16 ($P < 0.05$) in the primary analysis to $+0.095$ ($P < 0.01$) in the

deseasonalized analysis. This reflects the different ecological signals captured by the two metrics: the primary metric integrates shared seasonal covariation between GPP and EPE driven by light-temperature rhythms, whereas the deseasonalized metric isolates anomaly-scale covariation where greater persistence (higher AR(1)) can synchronize short-term fluctuations. The upstream VPD to AR(1) pathway remains robust (+0.20, $P < 0.01$), and the sign reversal highlights the scale-dependence of coupling metrics rather than contradicting the core mechanism.

While a non-significant χ^2 test ($P > 0.05$) is theoretically desired for model fit, χ^2 statistics are highly sensitive to sample size. Elevated χ^2/df values in strata with large sample sizes (Tropical: 10.87, $n = 2,021$; Temperate: 5.11, $n = 1,631$; Non-intact forests: 22.85, $n = 5,268$; Intact forests: 6.35, $n = 1,038$) reflect this sensitivity rather than substantive model misspecification. Incremental fit indices in these strata ($\text{CFI} \geq 0.98$, $\text{RMSEA} \leq 0.07$) remained within acceptable thresholds, confirming adequate model specification. In the Arid zone ($n = 73$), the small sample size produced a near-saturated model with unreliable fit index estimates (CFI and TLI not reported). Path coefficients in this stratum are reported for completeness but lack statistical power for reliable inference.

Overall, the sensitivity analysis confirms that our principal conclusions regarding the VPD-driven resilience-mediated pathway are robust to the treatment of seasonal variability.

SUPPLEMENTARY FIGURES

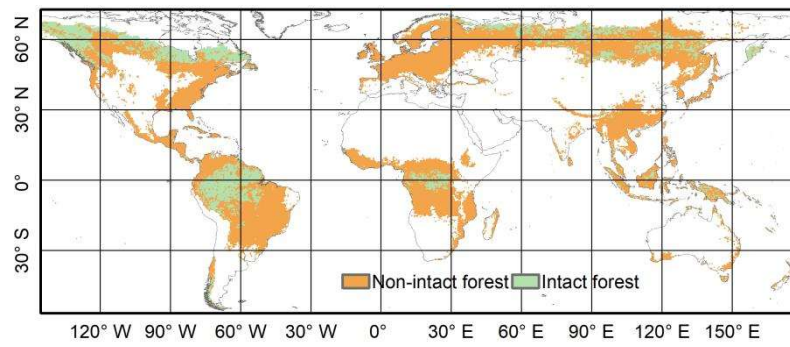


Fig. S1. Forest zoning map

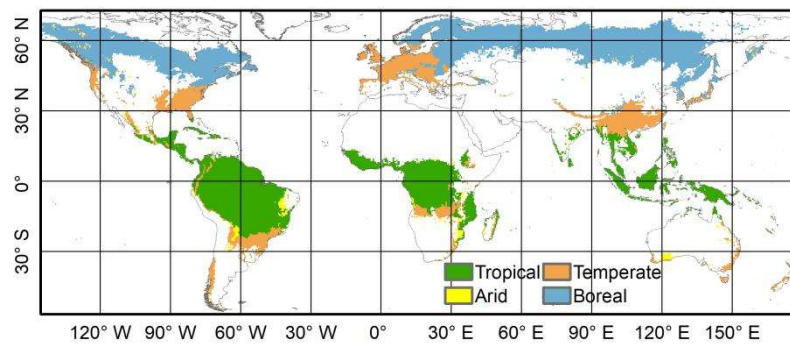


Fig. S2. Climate zoning map

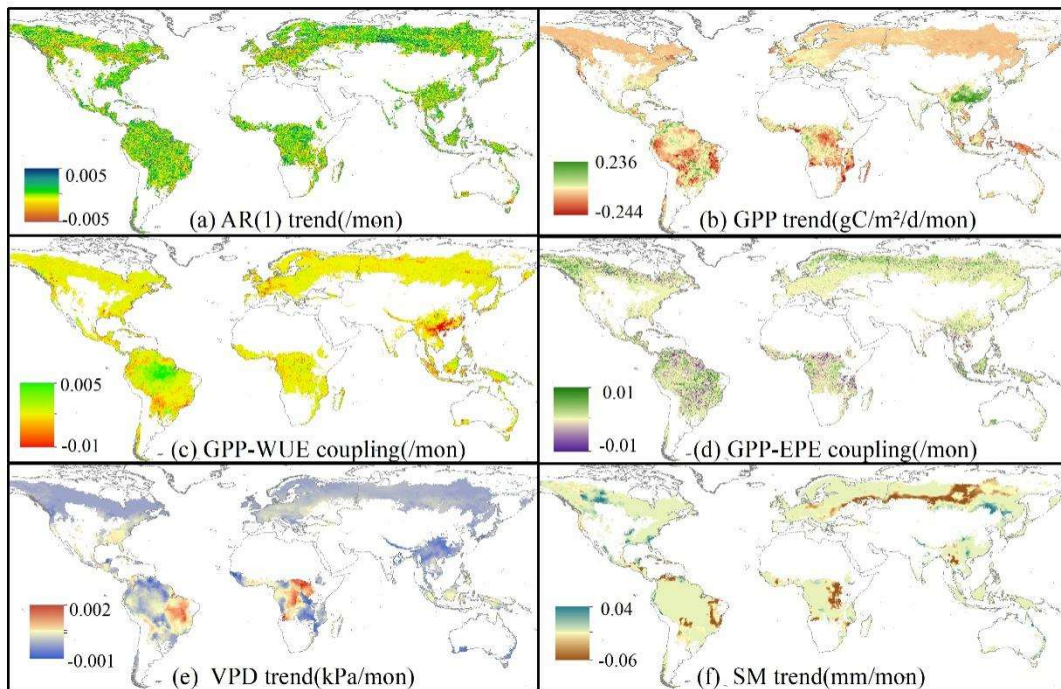


Fig. S3. Temporal dynamics of AR(1), GPP, functional coupling strength, VPD and SM

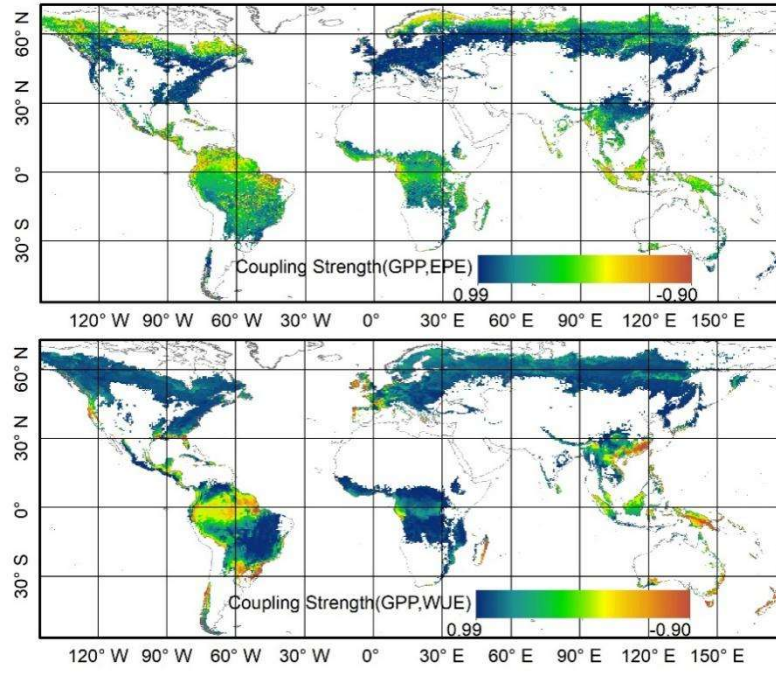


Fig. S4. Spatial patterns of the coupling strength of GPP-EPE and GPP-WUE from 2001 to 2021

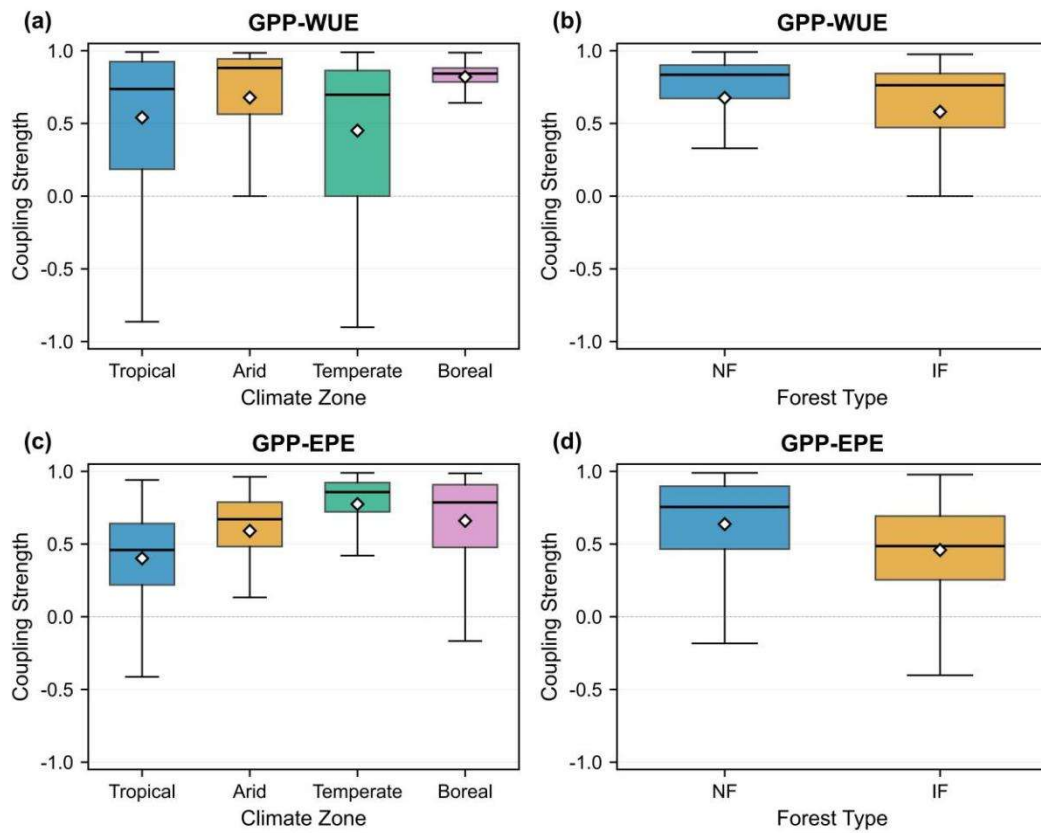


Fig. S5. Functional coupling of GPP with WUE and EPE across climate zones and forest types (NF indicates Non-intact forests, IF indicates Intact forests).

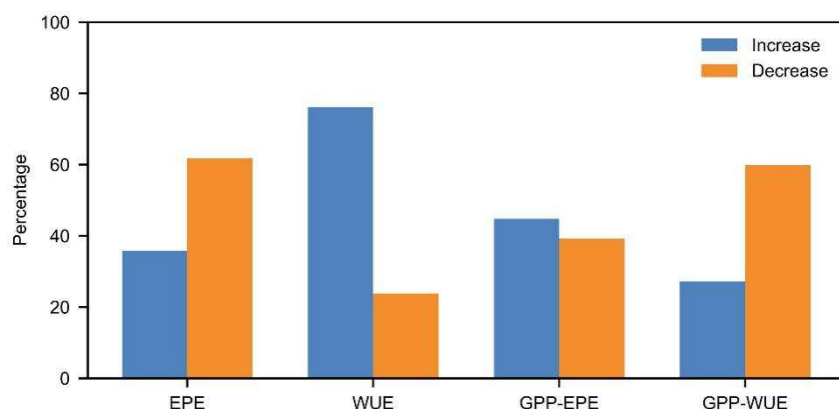


Fig. S6. Trends in EPE, WUE, coupling strength of GPP-EPE and coupling strength of GPP-WUE

SUPPLEMENTARY TABLES

Supplementary Table S1: Spearman correlations from binning analysis

SM decile	N	SM range (%)	Residual r	EPE~VPD r	P	WUE~VPD r	P
Q2	787	2.50–3.65	0.14	−0.01	7.47E−01	0.41	2.62E−33
Q3	787	3.65–4.85	0.03	−0.06	1.20E−01	0.28	8.26E−16
Q4	787	4.85–6.01	−0.06	0.03	4.86E−01	0.34	5.58E−23
Q5	788	6.01–7.05	−0.07	0.07	3.82E−02	0.38	1.42E−28
Q6	787	7.05–8.03	0.04	−0.02	5.23E−01	0.29	3.82E−17
Q7	787	8.03–9.19	0.11	−0.30	5.66E−18	0.4	4.40E−31
Q9	787	11.78–18.04	0.1	−0.10	5.19E−03	0.48	2.69E−47
Q10	788	18.08–47.09	0.01	0.1	7.64E−03	0.5	5.97E−50

VPD decile	N	VPD range (kPa)	Residual r	EPE~SM r	P	WUE~SM r	P
Q2	787	0.25–0.29	−0.01	0.1	7.92E−03	−0.08	1.91E−02
Q3	787	0.29–0.31	−0.03	0.36	6.01E−25	−0.21	2.20E−09
Q4	787	0.31–0.35	0.1	0.42	7.74E−35	−0.19	8.44E−08
Q5	788	0.35–0.42	−0.14	0.22	5.37E−10	−0.21	2.87E−09

VPD decile	N	VPD range (kPa)	Residual r	EPE~SM r	P	WUE~SM r	P
Q7	787	0.61–0.75	0.11	–0.18	5.06E–07	–0.23	1.27E–10
Q8	787	0.75–0.89	0.06	–0.13	2.46E–04	–0.22	1.20E–09
Q9	787	0.89–1.08	–0.01	–0.22	4.09E–10	–0.50	1.59E–50

Note: Spearman rank-order correlations between functional coupling strength and climate drivers across decile bins. (a) Independent effect of VPD: correlations with VPD within fixed soil moisture (SM) deciles. (b) Independent effect of SM: correlations with SM within fixed VPD deciles. To isolate these independent effects and minimize confounding collinearity, only deciles with weak residual VPD–SM correlations ($|r| < 0.15$) are shown. Bold values indicate statistical significance ($P < 0.05$, two-sided test, unadjusted for multiple comparisons). N represents the number of pixels per decile.

Supplementary Table S2: Model fit statistics for the structural equation models.

Zones	n	χ^2	χ^2/df	CFI	TLI	RMSEA	SRMR
Global forest	6733	1.3477	0.3369	1.000	1.002	0	0.0141
Tropical	2062	0.0013	0.0003	1.000	1.0087	0	0.001
Arid	77	0.8213	0.2053	1.000	1.2661	0	0.0018
Temperate	1673	0.7004	0.1751	1.000	1.0324	0	0.0017
Boreal	2869	6.258	1.5645	0.9976	0.9929	0.014	0.0467
Non-intact forests	5563	0.1673	0.0418	1.000	1.0039	0	0.0012
Intact forests	1170	0.5921	0.148	1.000	1.0065	0	0.0016

Note: Model fit was further evaluated using the chi-square to degrees of freedom ratio (χ^2/df), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Default outputs from the semopy package were used for these estimations.

Supplementary Table S3: SEM path coefficients under GLDAS soil moisture products

Standardized path coefficients from SEM under alternative soil moisture products.

(a) Standardized path coefficients

	Zones	VPD→AR(1)	SM→AR(1)	AR(1)→ GPP-EPE	AR(1)→ GPP-WUE	VPD→ GPP-EPE	SM→ GPP-EPE	VPD→ GPP-WUE	SM→ GPP-WUE
GLDAS 0-10cm	Tropical	0.275	-0.248	0.021	0.248	0.031	0.008	0.320	-0.261
	Arid	0.176	-0.386	-0.076	-0.042	0.077	-0.144	-0.085	0.358
	Temperate	0.209	-0.125	0.074	0.03	0.131	0.061	-0.065	-0.190
	Boreal	0.188	-0.063	-0.080	0.027	0.016	-0.019	0.333	-0.316
	Non-intact forests	0.472	-0.132	0.004	-0.084	0.069	0.011	-0.041	-0.199
	Intact forests	0.209	0.01	-0.097	0.068	0.048	-0.196	-0.656	-0.223
GLDAS 0-40cm	Tropical	0.289	-0.265	0.023	0.249	0.032	0.014	0.360	-0.220
	Arid	0.260	-0.329	-0.07	-0.068	0.11	-0.15	-0.161	0.345
	Temperate	0.204	-0.146	0.077	0.027	0.131	0.066	-0.055	-0.178
	Boreal	0.202	-0.021	-0.079	0.041	0.015	-0.03	0.360	-0.275
	Non-intact forests	0.498	-0.114	0.003	-0.084	0.066	0.003	-0.009	-0.198
	Intact forests	0.204	0.03	-0.092	0.074	0.075	-0.205	-0.622	-0.260
GLDAS 0-100cm	Tropical	0.288	-0.294	0.026	0.247	0.034	0.022	0.376	-0.197
	Arid	0.303	-0.302	-0.05	-0.081	0.117	-0.109	-0.215	0.358
	Temperate	0.200	-0.168	0.078	0.021	0.129	0.068	-0.053	-0.195
	Boreal	0.205	-0.01	-0.079	0.044	0.016	-0.027	0.369	-0.252
	Non-intact forests	0.519	-0.096	0.003	-0.085	0.066	0.002	0.022	-0.228
	Intact forests	0.202	0.026	-0.093	0.074	0.097	-0.206	-0.583	-0.298
GLDAS 0-200cm	Tropical	0.337	-0.190	0.022	0.284	0.032	0.015	0.401	-0.109
	Arid	0.282	-0.217	-0.04	-0.082	0.113	-0.099	-0.259	0.497
	Temperate	0.222	-0.116	0.073	0.034	0.125	0.058	-0.037	-0.152
	Boreal	0.206	-0.005	-0.079	0.045	0.018	-0.018	0.363	-0.273
	Non-intact forests	0.531	-0.034	0.002	-0.064	0.066	-0.002	0.042	-0.191
	Intact forests	0.208	0.005	-0.098	0.068	0.088	-0.192	-0.592	-0.301

(b) Significance (p-values) of the standardized path coefficients

	Zones	VPD→AR(1)	SM→AR(1)	AR(1)→ GPP-EPE	AR(1)→ GPP-WUE	VPD→ GPP-EPE	SM→ GPP-EPE	VPD→ GPP-WUE	SM→ GPP-WUE
GLDAS 0-10cm	Tropical	0.00E+00	0.00E+00	4.06E−01	0.00E+00	2.47E−01	7.77E−01	0.00E+00	0.00E+00
	Arid	9.05E−02	2.11E−04	5.49E−01	7.23E−01	5.12E−01	2.50E−01	4.36E−01	2.00E−03
	Temperate	2.66E−15	2.08E−06	3.93E−03	2.41E−01	2.49E−06	2.70E−02	1.85E−02	3.70E−12
	Boreal	0.00E+00	1.44E−03	4.20E−05	9.84E−02	4.26E−01	3.32E−01	0.00E+00	0.00E+00
	Non-intact forests	0.00E+00	0.00E+00	7.94E−01	1.63E−07	4.52E−05	4.68E−01	1.51E−02	0.00E+00
	Intact forests	5.48E−13	7.31E−01	1.05E−03	1.78E−03	1.02E−01	1.31E−11	0.00E+00	0.00E+00
GLDAS 0-40cm	Tropical	0.00E+00	0.00E+00	3.67E−01	0.00E+00	2.10E−01	5.88E−01	0.00E+00	0.00E+00
	Arid	1.51E−02	2.10E−03	5.74E−01	5.55E−01	3.58E−01	2.18E−01	1.47E−01	2.40E−03
	Temperate	4.66E−15	1.77E−08	2.95E−03	2.93E−01	1.90E−06	1.49E−02	4.51E−02	4.52E−11
	Boreal	0.00E+00	2.83E−01	4.90E−05	1.52E−02	4.55E−01	1.29E−01	0.00E+00	0.00E+00
	Non-intact forests	0.00E+00	0.00E+00	8.55E−01	1.72E−07	5.53E−05	8.20E−01	5.84E−01	0.00E+00
	Intact forests	3.56E−12	3.01E−01	1.84E−03	5.89E−04	1.18E−02	3.02E−12	0.00E+00	0.00E+00
GLDAS 0-100cm	Tropical	0.00E+00	0.00E+00	3.13E−01	0.00E+00	1.85E−01	3.85E−01	0.00E+00	0.00E+00
	Arid	6.82E−03	7.05E−03	6.83E−01	4.77E−01	3.49E−01	3.84E−01	6.27E−02	1.94E−03
	Temperate	4.22E−15	4.49E−11	2.56E−03	4.25E−01	1.82E−06	1.15E−02	4.66E−02	3.10E−13
	Boreal	0.00E+00	6.00E−01	5.10E−05	9.58E−03	4.27E−01	1.67E−01	0.00E+00	0.00E+00
	Non-intact forests	0.00E+00	2.22E−16	8.60E−01	1.01E−07	4.91E−05	8.98E−01	1.68E−01	0.00E+00
	Intact forests	2.06E−11	3.83E−01	1.58E−03	5.17E−04	1.50E−03	7.25E−12	0.00E+00	0.00E+00
GLDAS 0-200cm	Tropical	0.00E+00	0.00E+00	3.75E−01	0.00E+00	2.12E−01	5.48E−01	0.00E+00	1.00E−08
	Arid	1.43E−02	5.98E−02	7.42E−01	4.30E−01	3.64E−01	4.18E−01	1.58E−02	2.66E−06
	Temperate	0.00E+00	5.12E−06	4.26E−03	1.81E−01	3.30E−06	2.81E−02	1.63E−01	9.15E−09
	Boreal	0.00E+00	8.01E−01	5.50E−05	7.32E−03	3.69E−01	3.52E−01	0.00E+00	0.00E+00
	Non-intact forests	0.00E+00	3.47E−03	8.84E−01	6.40E−05	5.30E−05	9.05E−01	7.75E−03	0.00E+00
	Intact forests	2.98E−12	8.64E−01	9.83E−04	4.02E−03	1.11E−10	1.33E−03	0.00E+00	0.00E+00

Note: The significance of individual path coefficients was evaluated using two-sided Z-tests, with $P < 0.05$ indicating a statistically significant effect, unadjusted for multiple comparisons. Overall model fit was assessed using a one-sided chi-square (χ^2) goodness-of-fit test, where a non-significant result ($P > 0.05$) theoretically indicates adequate fit. Default outputs from the semopy package were used for these estimations.

Supplementary Table S4: SEM path coefficients and model fit statistics using deseasonalized coupling metrics

(a) Standardized path coefficients								
Zones	VPD→AR(1)	SM→AR(1)	AR(1)→ GPP-EPE	AR(1)→ GPP-WUE	VPD→ GPP-EPE	SM→ GPP-EPE	VPD→ GPP-WUE	SM→ GPP-WUE
Tropical	0.367	−0.137	0.293	0.289	−0.070	−0.051	0.439	−0.167
Arid	0.053	−0.305	0.176	−0.01	0.067	−0.084	0.024	0.052
Temperate	0.302	−0.175	0.281	0.366	−0.150	−0.081	0.221	−0.187
Boreal	0.201	−0.094	0.095	0.107	0.048	0.249	0.302	−0.209
Non-intact forests	0.560	−0.113	0.186	0.218	−0.347	−0.106	0.368	−0.248
Intact forests	0.269	−0.103	0.149	0.094	−0.336	−0.062	−0.067	−0.330

(b) Significance (p-values) of the standardized path coefficients								
Zones	VPD→ AR(1)	SM→ AR(1)	AR(1)→ GPP-EPE	AR(1)→ GPP-WUE	VPD→ GPP-EPE	SM→ GPP-EPE	VPD→ GPP-WUE	SM→ GPP-WUE
Tropical	0.00E+00	1.75E−11	0.00E+00	0.00E+00	2.54E−03	1.84E−02	0.00E+00	0.00E+00
Arid	6.41E−01	6.81E−03	1.42E−01	9.36E−01	5.62E−01	4.85E−01	8.37E−01	6.73E−01
Temperate	0.00E+00	3.41E−13	0.00E+00	0.00E+00	2.77E−09	9.49E−04	0.00E+00	0.00E+00
Boreal	0.00E+00	1.03E−06	1.20E−06	8.92E−09	1.44E−02	0.00E+00	0.00E+00	0.00E+00
Non-intact forests	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.17E−14	0.00E+00	0.00E+00
Intact forests	4.88E−11	1.19E−02	4.08E−07	1.41E−03	0.00E+00	1.10E−01	9.06E−02	0.00E+00

(c) Model fit statistics							
Zones	n	χ^2	χ^2/df	CFI	TLI	RMSEA	SRMR
Tropical	2021.00	43.48	10.87	0.98	0.93	0.07	0.08
Arid	73.00	0.30	0.07	-	-	0.00	0.00
Temperate	1631.00	20.44	5.11	0.98	0.95	0.05	0.08
Boreal	2548.00	8.92	2.23	0.99	0.98	0.02	0.06
Non-intact forests	5268.00	91.42	22.85	0.98	0.95	0.06	0.08
Intact forests	1038.00	25.39	6.35	0.98	0.94	0.07	0.08

Note: Standardized path coefficients from structural equation models fitted using deseasonalized coupling metrics derived from STL residuals. The significance of individual path coefficients was evaluated using two-sided Z-tests, with $P < 0.05$ indicating a statistically significant effect. Overall model fit was assessed using a one-sided chi-square (χ^2) goodness-of-fit test, where a non-significant result ($P > 0.05$) theoretically indicates adequate fit. Model fit was further evaluated using the chi-square to degrees of freedom ratio (χ^2/df), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Default outputs from the semopy package were used for these estimations.