

Functional composition and structural diversity enhance mangrove forest resilience in the Sundarbans

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Supplementary

Table S1: Fit statistics for six fitted structural equation models. 3 for λ_{AC1} and 3 for λ_{VAR} with three disturbance related variables (*PF*, *ADI*, and *WDI*) separately along with 13 biotic and abiotic variables.

Model	Resilience	Disturbance	χ^2	df	pvalue	CFI	GFI	SRMR	AIC	R ²
λ_{ac1_PF}	λ_{ac1}	PF	2.489	2	0.288	0.999	0.997	0.009	3786.92	0.44
λ_{ac1_ADDI}	λ_{ac1}	ADDI	2.769	2	0.25	0.999	0.996	0.01	3805.78	0.45
λ_{ac1_WDI}	λ_{ac1}	WDI	2.795	2	0.247	0.999	0.996	0.01	3805.66	0.43
λ_{var_PF}	λ_{var}	PF	2.489	2	0.288	0.999	0.997	0.009	3776.63	0.49
λ_{var_ADDI}	λ_{var}	ADDI	2.769	2	0.25	0.999	0.996	0.01	3805.69	0.45
λ_{var_WDI}	λ_{var}	WDI	2.795	2	0.247	0.999	0.996	0.01	3806.15	0.43

The non-significant χ^2 (Chi-Square) with ($P > 0.05$), with a goodness of fit index (GFI) close 1, with a comparative fit index close to 1 and a standardized root mean square residual < 0.05 , suggests no significant deviation from the model and datasets at 2 degrees of freedom. While a higher R² (Coefficient of Determination within the endogenous variables represent their explained variance by all predictors) and a lower Akaike Information Criterion (AIC) define the model selection. The predictors were *MAP* Mean annual precipitation, *MAT* Mean annual temperature, *SS* Sediment salinity, *Sedimen SR* Species richness, *FC MCH* functional composition of maximum canopy height, *SD* Structural diversity (coefficient of variance of diameter at breast height), *FCSLA* Functional composition Specific leaf area, *FDSC* Functional diversity leaf succulence, *P* Sediment Phosphorus concentration, *SF* Sediment Iron concentration, *SSF* Sediment sulfide concentration, *pH* Sediment pH level, *STS* Sediment texture silt, *PF* perturbation frequency, *ADI*, average drop disturbance index, and *WDI*, Weighted average drop disturbance index. Response or endogenous variable were λ_{VAR} Recovery rate Lambda variance, λ_{AC1} Recovery rate Lambda 1-lag autocorrelation.

Table S2. Variance inflation factors test to remove highly correlated variables (functional diversity of traits). Multiple linear regression (Resilience used as response variable) was used where regression started by including all the covariates and gradually removes the variable with highest variance inflation factor until achieving the threshold value. Covariates with a variance inflation factor below 10 (threshold value) do not imply multicollinearity.

FDSL	FDDL	FDSC	FDLPR	FDLDMC	FDMCH	FDWD
11.02	2.59	9.16	72.98	85.91	13.50	42.56
10.96	2.30	8.75	23.36	NA	10.90	24.11
2.41	1.97	6.89	17.92	NA	8.01	NA
2.04	1.49	3.40	NA	NA	2.68	NA

FD Functional diversity, *SLA* leaf area, *LLN* leaf litter nitrogen, *SC* leaf succulence, *PSR* Leaf photosynthesis rate, *LDMC* Leaf dry matter content, *MCH* Maximum canopy height, *WD* Wood density

Table S3. Variance inflation factors test to remove highly correlated covariables (functional composition of traits). Multiple linear regression (Resilience used as response variable) was used where regression started by including all the covariates and gradually removes the variable with highest variance inflation factor until achieving the threshold value. Covariates with a variance inflation factor below 10 (threshold value) do not imply multicollinearity.

Regression steps	CWM SLA	CWM LLN	CWM SC	CWM LPR	CWM LDMC	CWM MCH	CWM WD
1	38.82	7.07	38.09	244.68	638.74	32.20	165.26
2	27.74	6.84	31.46	131.23	NA	31.67	66.49
3	27.08	5.69	29.07	NA	NA	8.45	46.89
4	11.47	5.50	14.49	NA	NA	8.02	NA
5	5.12	3.42	NA	NA	NA	7.24	NA

FC Functional composition, *SLA* Specific leaf area, *LLN* leaf litter nitrogen, *SC* leaf succulence, *PSR* Leaf photosynthesis rate, *LDMC* Leaf dry matter content, *MCH* Maximum canopy height, *WD* Wood density

Table S4. Result of variance inflation factor test for checking multicollinearity using multiple linear regression (Resilience used as response variable) among the covariates in the accepted structural equation model. Covariates with a value below 10 do not imply multicollinearity.

Variable	Variance inflation factor
Functional composition maximum canopy height	4.57
Functional composition specific leaf area	5.09
Functional diversity leaf succulence	1.57
Structural diversity (Diameter at breast height ≥ 1.30 cm)	2.13
Species richness	1.73
Sediment sulfide	3.10
Sediment phosphorus	1.79
Sediment iron	2.13
Sediment pH	1.34
Sediment texture silt	1.20
Sediment salinity	2.94
Perturbation frequency	1.32
Mean annual precipitation	3.81
Mean annual temperature	3.56

Table S5: Relative abundance of plant and their corresponding functional traits in the Sundarbans

RA Relative abundance^{1,2}, *LS* Leaf succulence³, *LDMC* Leaf dry matter content³, *SLA* Specific leaf area³, *LLN* Leaf litter nitrogen⁴, *LPSR* Leaf photosynthesis rate⁵, *MCH* Maximum canopy height², Wood density⁶

Scientific name	RA	LS (g m ⁻²)	LDMC (g g ⁻¹)	SLA (cm ² g ⁻¹)	LLN (%)	LPSR (μmolm ⁻² s ⁻¹)	MCH (m)	WD (gcm ⁻³)
<i>Heritiera fomes</i>	52.95	179.75	507.30	63.17	1.43	13.21	38.50	1.07
<i>Excoecaria agallocha</i>	41.05	273.43	219.08	135.49	1.32	7.02	31.00	0.45
<i>Bruguiera sexangula</i>	2.42	248.76	281.35	112.22	1.22	5.89	21.00	0.86
<i>Xylocarpus mekongensis</i>	1.41	204.30	317.00	98.74	1.86	6.68	16.50	0.73
<i>Avicennia officinalis</i>	0.71	244.69	298.15	91.04	1.94	8.39	31.30	0.67
<i>Amoora cuculata</i>	0.42	208.93	405.80	73.08	1.86	6.41	21.50	0.66
<i>Xylocarpus granatum</i>	0.42	278.52	261.08	95.89	2.34	3.47	18.00	0.70
<i>Intsia bijuga</i>	0.2	165.68	352.44	125.85	1.86	6.41	10.60	0.80
<i>Sonneratia apetala</i>	0.07	369.68	266.42	65.76	1.84	6.41	29.90	0.56
<i>Sonneratia caseolaris</i>	0.07	465.00	317.00	98.74	2.63	12.75	10.00	0.50
<i>Cynometra ramiflora</i>	0.06	80.18	555.51	103.66	1.86	6.41	13.90	0.90
<i>Aegiceras corniculatum</i>	0.05	272.25	258.04	88.76	1.11	6.75	9.80	0.64
<i>Unknown species</i>	0.05	331.85	262.19	81.60	2.97	5.36	26.40	0.73
<i>E. indica</i>	0.04	116.07	374.97	162.00	1.86	6.41	15.00	0.65
<i>Pongamia pinnata</i>	0.04	109.79	360.39	167.21	1.86	6.41	18.50	0.67
<i>Rhizophora mucronata</i>	0.04	299.43	319.49	27.61	0.92	5.72	16.50	1.02
<i>Hibiscus tiliaceus</i>	0.01	245.09	285.66	144.90	1.86	6.41	7.80	0.60
<i>Lumnitzera racemosa</i>	0	193.50	550.00	98.07	1.96	9.37	16.00	0.73

Table S6 List of cyclones formed in the Bay of Bengal from 2000-2024. A total 34 cyclone formed over this 25 years period⁷⁻⁹.

Name	Date	Max Winds (km/h)	Category	Landfall Location
C00 (Unnamed)	27/10/2000	55	Cyclonic Storm	Odisha, India (near Paradip)
C02 (Unnamed)	12/11/2002	65	Severe Cyclonic Storm	Andhra Pradesh, India (near Kakinada)
C04 (Unnamed)	15/05/2004	50	Cyclonic Storm	Bangladesh (near Chittagong)
C05 (Unnamed)	01/10/2005	100	Very Severe Cyclonic Storm	Tamil Nadu, India (near Nagapattinam)
C06 (Unnamed)	30/06/2006	75	Severe Cyclonic Storm	Odisha, India (near Puri)
Sidr	15/11/2007	260	Super Cyclonic Storm	Bangladesh (Khulna Division, near Bhola Island)
Nargis	02/05/2008	215	Extremely Severe Cyclonic Storm	Myanmar (Irrawaddy Delta, near Labutta)
Rashmi	26/10/2008	60	Severe Cyclonic Storm	Bangladesh (Chittagong coast)
Aila	25/05/2009	100	Very Severe Cyclonic Storm	West Bengal & Bangladesh (Sundarbans)
Laila	27/05/2010	105	Very Severe Cyclonic Storm	Andhra Pradesh, India (near Machilipatnam)
Jal	01/11/2010	120	Extremely Severe Cyclonic Storm	Andhra Pradesh, India (near Kakinada)
Thane	30/12/2011	110	Extremely Severe Cyclonic Storm	Maharashtra, India (near Mumbai/Thane)
Nilam	30/10/2012	85	Very Severe Cyclonic Storm	Tamil Nadu, India (near Nagapattinam)
Phailin	12/10/2013	215	Super Cyclonic Storm	Odisha, India (near Gopalpur)
Helen	19/11/2013	100	Very Severe Cyclonic Storm	Andhra Pradesh, India (near Bapatla)
Hudhud	12/10/2014	185	Super Cyclonic Storm	Andhra Pradesh, India (near Visakhapatnam)
Komen	27/07/2015	75	Severe Cyclonic Storm	Bangladesh (Cox's Bazar)
Roanu	21/05/2016	95	Very Severe Cyclonic Storm	Bangladesh (Chittagong coast)
Vardah	12/12/2016	155	Super Cyclonic Storm	Tamil Nadu, India (near Chennai)
Mora	30/05/2017	110	Extremely Severe Cyclonic Storm	Bangladesh (Sylhet/Brahmanbaria coast)
Ockhi	29/12/2017	145	Super Cyclonic Storm	Gujarat, India (near Porbandar)
Titli	11/10/2018	140	Super Cyclonic Storm	Andhra Pradesh, India (near Palasa)
Fani	03/05/2019	205	Super Cyclonic Storm	Odisha, India (near Puri)
Bulbul	09/11/2019	120	Extremely Severe Cyclonic Storm	West Bengal & Bangladesh (Sundarbans)
Amphan	20/05/2020	240	Super Cyclonic Storm	West Bengal & Bangladesh (Sundarbans)
Yaas	26/05/2021	140	Super Cyclonic Storm	Odisha & West Bengal (near Balasore)
Jawad	06/12/2021	85	Very Severe Cyclonic Storm	Andhra Pradesh, India (near Kakinada)
Asani	11/05/2022	110	Extremely Severe Cyclonic Storm	Andhra Pradesh, India (near Srikakulam)
Sitrang	24/10/2022	90	Very Severe Cyclonic Storm	Bangladesh (Chittagong coast)
Mandous	06/12/2022	85	Very Severe Cyclonic Storm	Tamil Nadu, India (near Mahabalipuram)
Mocha	14/05/2023	165	Super Cyclonic Storm	Myanmar (Rakhine State, near Maungdaw)
Hamoon	24/10/2023	115	Extremely Severe Cyclonic Storm	Pakistan (Sindh coast, near Karachi)
Midhili	17/11/2023	80	Severe Cyclonic Storm	Bangladesh (Cox's Bazar)
Remal	26/05/2024	120	Extremely Severe Cyclonic Storm	West Bengal & Bangladesh (Sundarbans)

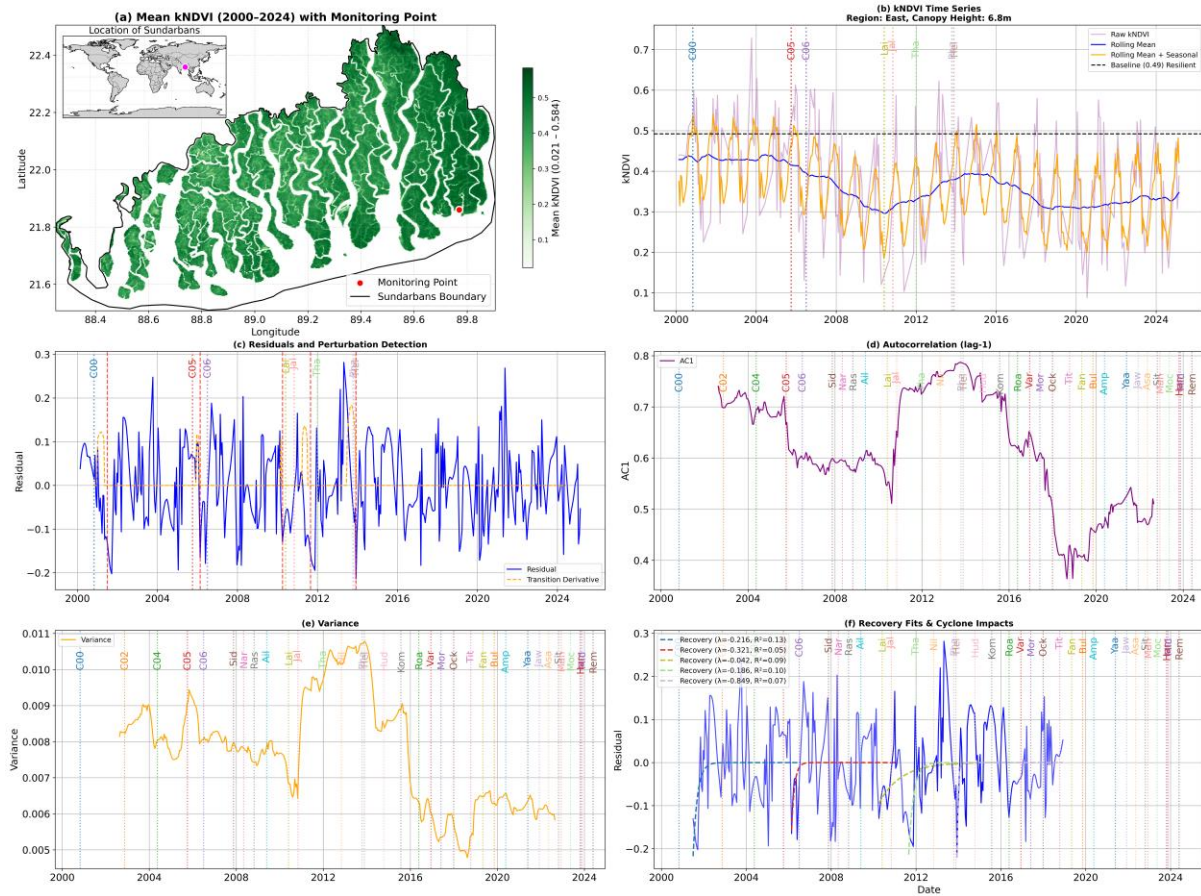


Fig. S1 Vegetation dynamics and resilience indicators in the Sundarbans. (a) Long term Mean kNDVI (2000–2020) in Sundarbans with monitoring points (21.86, 89.77) and boundary; (b) kNDVI time series the particular monitoring site in eastern region, showing raw and smoothed kNDVI values, with cyclone impact periods marked; (c) Perturbation detection by 12 months moving window approaches and 95 percent thresholding on residual time series, highlighting perturbation periods; (d) Temporal one-lag autocorrelation of residual kNDVI, signaling the resilience loss or critical slowing down; (e) Variance in residuals captures fluctuations in the kNDVI time series, with detected perturbations flagged, showcasing critical slowing down; (f) Empirical post-disturbance recovery rate trajectories from local minima, following cyclone impacts, indicating vegetation response and resilience over time. The magenta circle on the global map (a) shows the position of the Sundarbans on the Globe. C00 (Unnamed), C02 (Unnamed), C04 (Unnamed), C05 (Unnamed), C06 (Unnamed), Sid Sidr, Nar Nargis, Ras Rashmi, Ail Aila, Lai Laila, Jal Jal, Tha Thane, Nil Nilam, Pha Phailin, Hel Helen, Hud Hudhud, Kom Komen, Roa Roanu, Var Vardah, Mor Mora, Ock Ockhi, Tit Titli, Fan Fani, Bul Bulbul, Amp Amphan, Yaa Yaas, Jaw Jawad, Asa Asani, Sit Sitrang, Man Mandous, Moc Mocha, Ham Hamoon, Mid Midhili, Rem Remal.

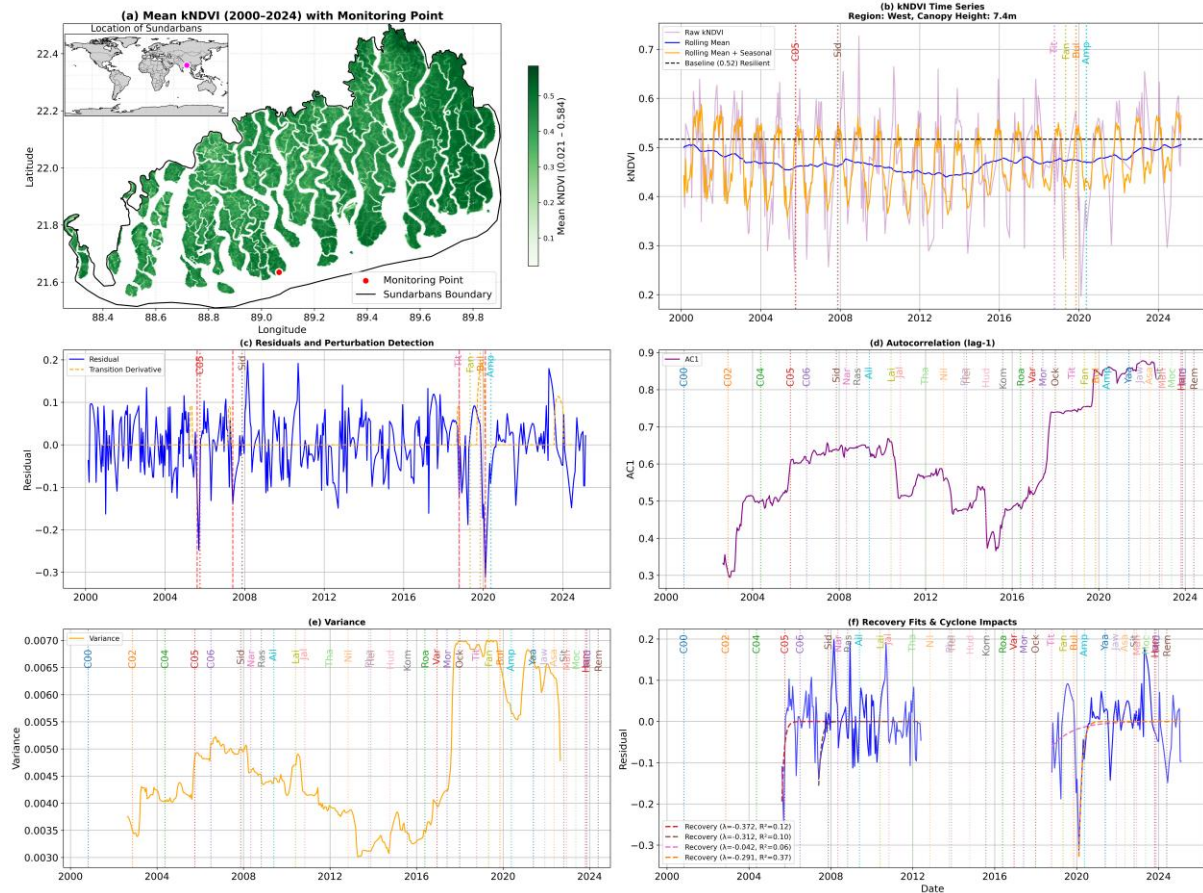


Fig. S2 Vegetation dynamics and resilience indicators in the Sundarbans. (a) Long term Mean kNDVI (2000–2020) in Sundarbans with monitoring points (21.634621, 89.066211) and boundary; (b) kNDVI time series the particular monitoring site in eastern region, showing raw and smoothed kNDVI values, with cyclone impact periods marked; (c) Perturbation detection by 12 months moving window approaches and 95 percent thresholding on residual time series, highlighting perturbation periods; (d) Temporal one-lag autocorrelation of residual kNDVI, signaling the resilience loss or critical slowing down; (e) Variance in residuals captures fluctuations in the kNDVI time series, with detected perturbations flagged, showcasing critical slowing down; (f) Empirical post-disturbance recovery rate trajectories from local minima, following cyclone impacts, indicating vegetation response and resilience over time. The magenta circle on the global map (a) shows the position of the Sundarbans on the Globe. C00 (Unnamed), C02 (Unnamed), C04 (Unnamed), C05 (Unnamed), C06 (Unnamed), Sid Sidr, Nar Nargis, Ras Rashmi, Ail Aila, Lai Laila, Jal Jal, Tha Thane, Nil Nilam, Pha Phailin, Hel Helen, Hud Hudhud, Kom Komen, Roa Roanu, Var Vardah, Mor Mora, Ock Ockhi, Tit Titli, Fan Fani, Bul Bulbul, Amp Amphan, Yaa Yaas, Jaw Jawad, Asa Asani, Sit Sitrang, Man Mandous, Moc Mocha, Ham Hamoon, Mid Midhili, Rem Remal.

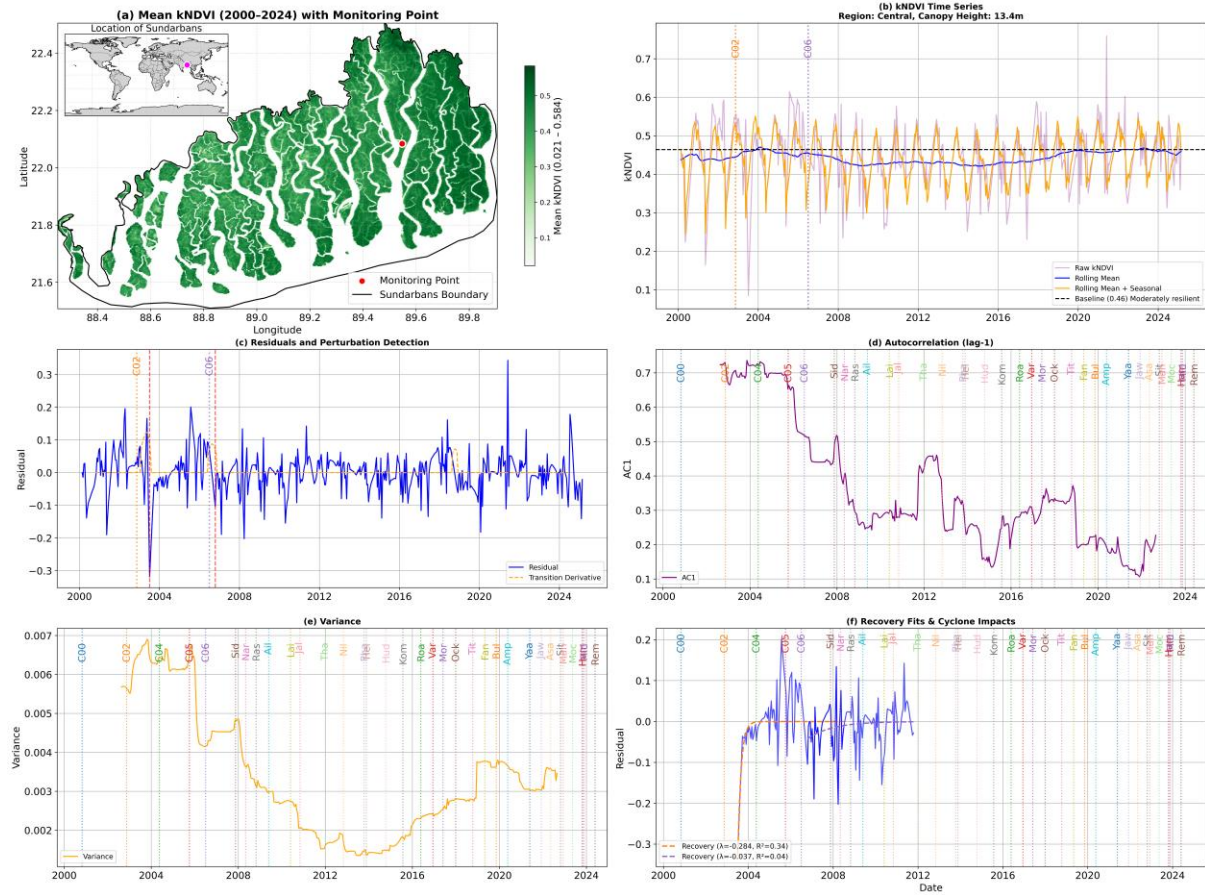


Fig. S3 Vegetation dynamics and resilience indicators in the Sundarbans. (a) Long term Mean kNDVI (2000–2020) in Sundarbans with monitoring points (89.547263, 22.084194) and boundary; (b) kNDVI time series the particular monitoring site in eastern region, showing raw and smoothed kNDVI values, with cyclone impact periods marked; (c) Perturbation detection by 12 months moving window approaches and 95 percent thresholding on residual time series, highlighting perturbation periods; (d) Temporal one-lag autocorrelation of residual kNDVI, signaling the resilience loss or critical slowing down; (e) Variance in residuals captures fluctuations in the kNDVI time series, with detected perturbations flagged, showcasing critical slowing down; (f) Empirical post-disturbance recovery rate trajectories from local minima, following cyclone impacts, indicating vegetation response and resilience over time. The magenta circle on the global map (a) shows the position of the Sundarbans on the Globe. C00 (Unnamed), C02 (Unnamed), C04 (Unnamed), C05 (Unnamed), C06 (Unnamed), Sid Sidr, Nar Nargis, Ras Rashmi, Ail Aila, Lai Laila, Jal Jal, Tha Thane, Nil Nilam, Pha Phailin, Hel Helen, Hud Hudhud, Kom Komen, Roa Roanu, Var Vardah, Mor Mora, Ock Ockhi, Tit Titli, Fan Fani, Bul Bulbul, Amp Amphan, Yaa Yaas, Jaw Jawad, Asa Asani, Sit Sitrang, Man Mandous, Moc Mocha, Ham Hamoon, Mid Midhili, Rem Remal.

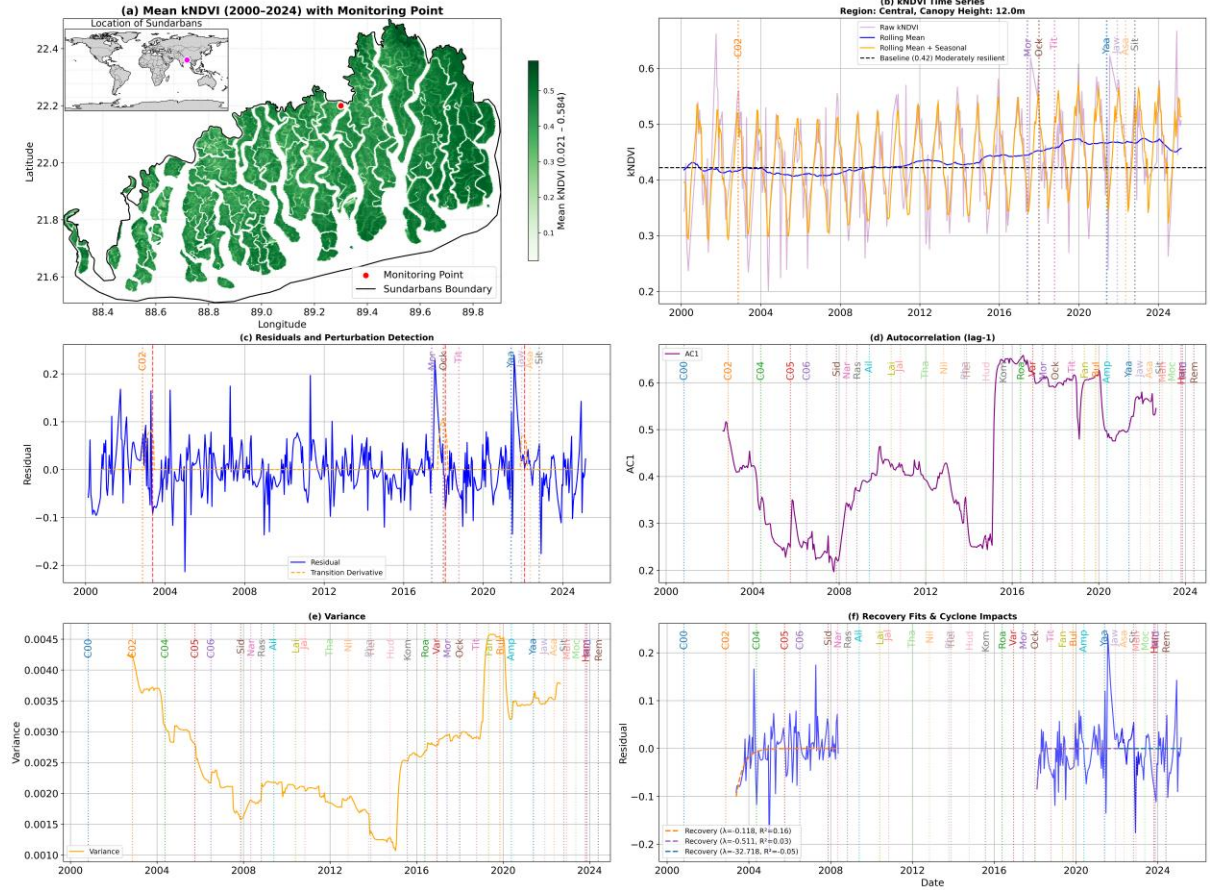


Fig. S4. Vegetation dynamics and resilience indicators in the Sundarbans. (a) Long term Mean kNDVI (2000–2020) in Sundarbans with monitoring points (89.30, 22.20) and boundary; (b) kNDVI time series the particular monitoring site in eastern region, showing raw and smoothed kNDVI values, with cyclone impact periods marked; (c) Perturbation detection by 12 months moving window approaches and 95 percent thresholding on residual time series, highlighting perturbation periods; (d) Temporal one-lag autocorrelation of residual kNDVI, signaling the resilience loss or critical slowing down; (e) Variance in residuals captures fluctuations in the kNDVI time series, with detected perturbations flagged, showcasing critical slowing down; (f) Empirical post-disturbance recovery rate trajectories from local minima, following cyclone impacts, indicating vegetation response and resilience over time. The magenta circle on the global map (a) shows the position of the Sundarbans on the Globe. C00 (Unnamed), C02 (Unnamed), C04 (Unnamed), C05 (Unnamed), C06 (Unnamed), Sid Sidr, Nar Nargis, Ras Rashmi, Ail Aila, Lai Laila, Jal Jal, Tha Thane, Nil Nilam, Pha Phailin, Hel Helen, Hud Hudhud, Kom Komen, Roa Roanu, Var Vardah, Mor Mora, Ock Ockhi, Tit Titli, Fan Fani, Bul Bulbul, Amp Amphan, Yaa Yaas, Jaw Jawad, Asa Asani, Sit Sitrang, Man Mandous, Moc Mocha, Ham Hamoon, Mid Midhili, Rem Remal.

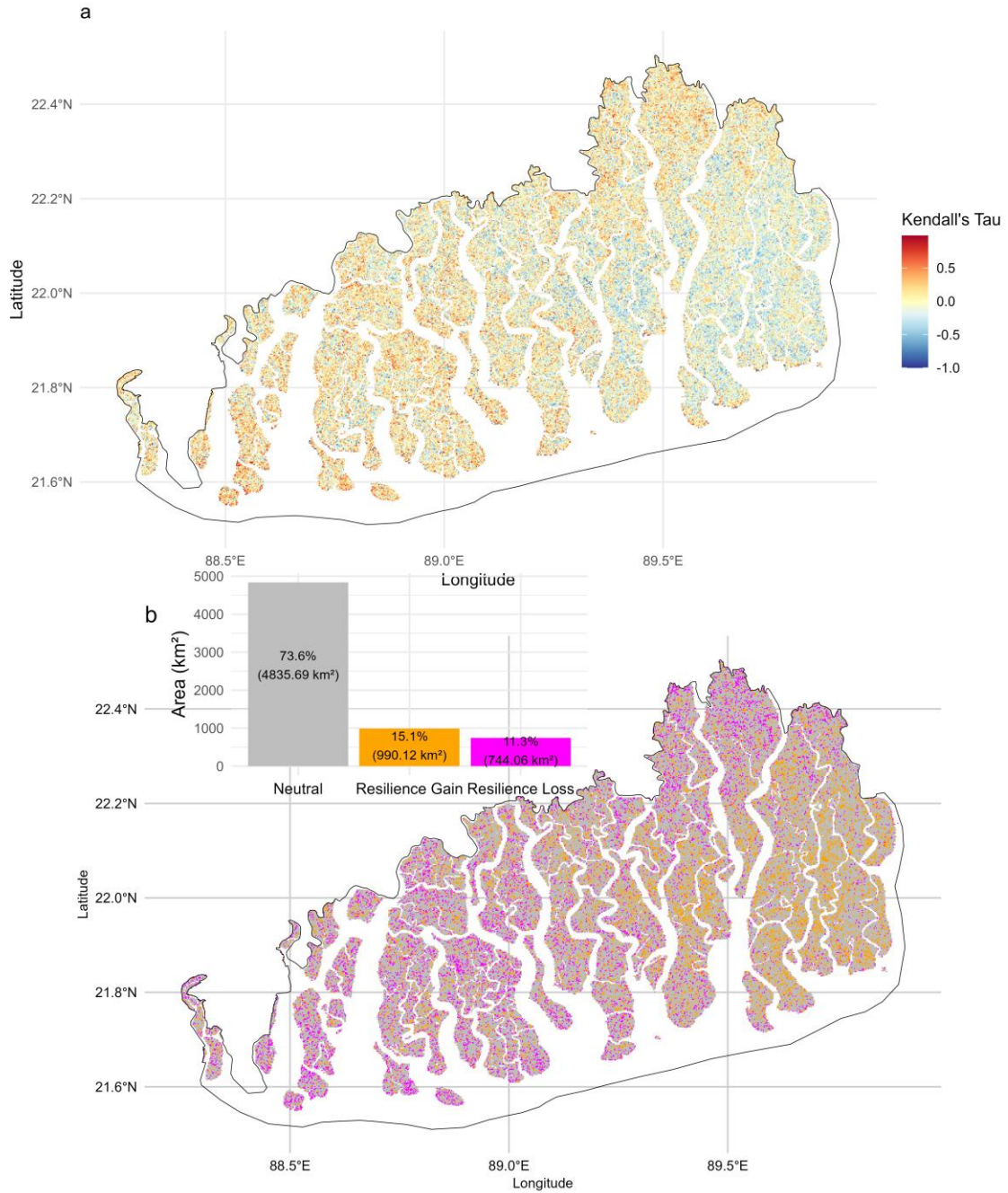


Fig. S5: Spatial pattern of forest resilience trends (3 years overlapping window) in the Sundarbans from 2000 to 2024. a spatial pattern of Kendall's Tau of resilience, **b** significant trend of Kendall's tau of resilience with area coverage of forest stands under the three-significance level of Kendall's tau. Significant positive trends ($p < 0.05$, magenta) indicate resilience loss, while negative trends ($p < 0.05$, orange) indicate resilience gain. Insignificant trends ($p > 0.05$, grey) reveal neutral and less sensitive changes to disturbance.

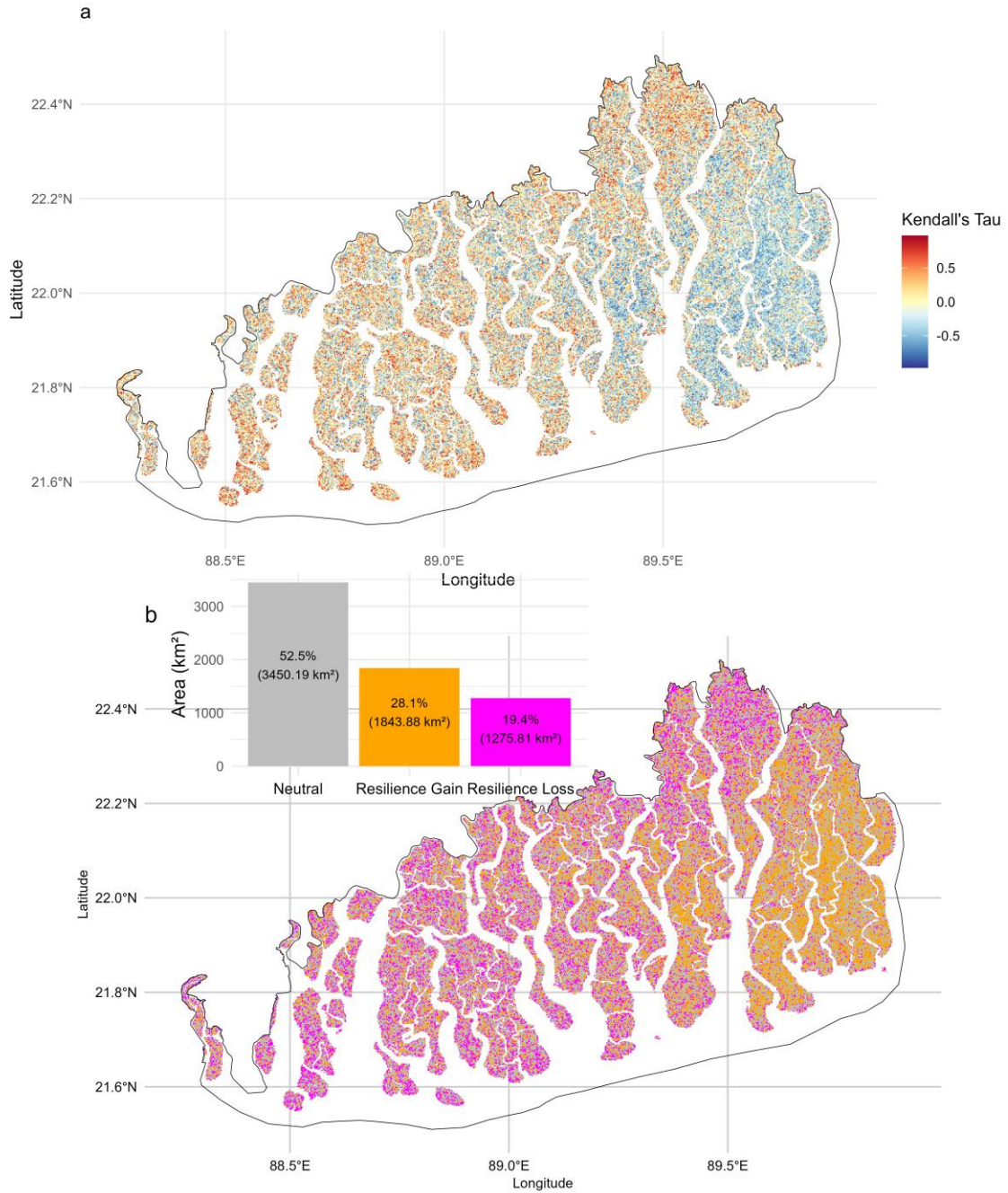


Fig. S6: Spatial pattern of forest resilience trends (7 years overlapping window) in the Sundarbans from 2000 to 2024. a spatial pattern of Kendall's Tau of resilience, **b** significant trend of Kendall's tau of resilience with area coverage of forest stands under the three-significance level of Kendall's tau. Significant positive trends ($p < 0.05$, magenta) indicate resilience loss, while negative trends ($p < 0.05$, orange) indicate resilience gain. Insignificant trends ($p > 0.05$, grey) reveal neutral and less sensitive changes to disturbance.

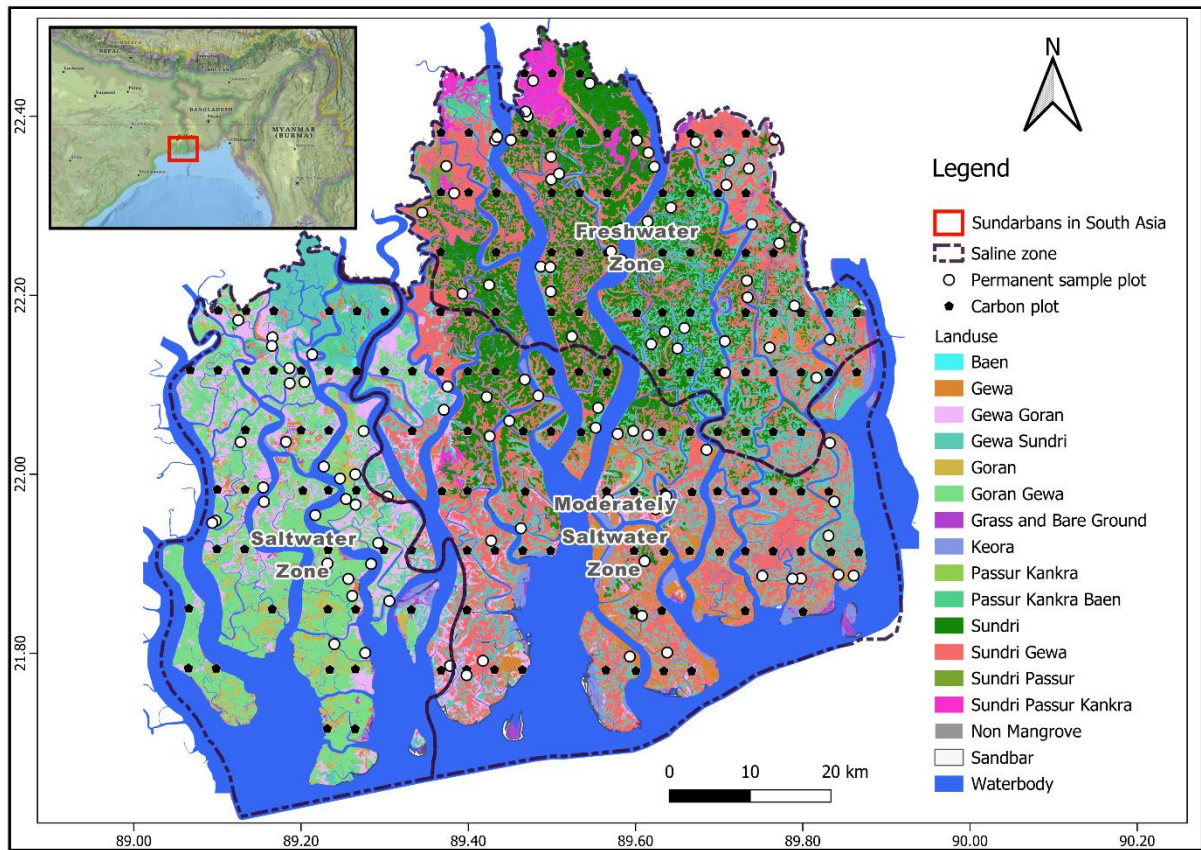


Fig S7. Sundarbans Reserved Forest vegetation with salinity zone, carbon plot and permanent sample plots. Sediment properties were taken from Sarkar et al. 2016, which were surveyed during January – June 2014 at 110 Permanent Sample Plots (white circle) distributed across different vegetation type in Sundarbans. Forest carbon inventory plots (155 plots, five were under water; Black pentagon) also spread across different vegetation types were collected from Bangladesh Forest Department tree data we used in the study Map produced in Quantum Geographic Information System (Version 3.40). Open-Source Geospatial Foundation. <https://qgis.org>. Source of Land use is Centre for Environmental and Geographic Information Services, Bangladesh. The inset image source is Food and Agricultural Organization,

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