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Responses of ecosystem productivity to aerosols across India: a double-edged sword in climate change

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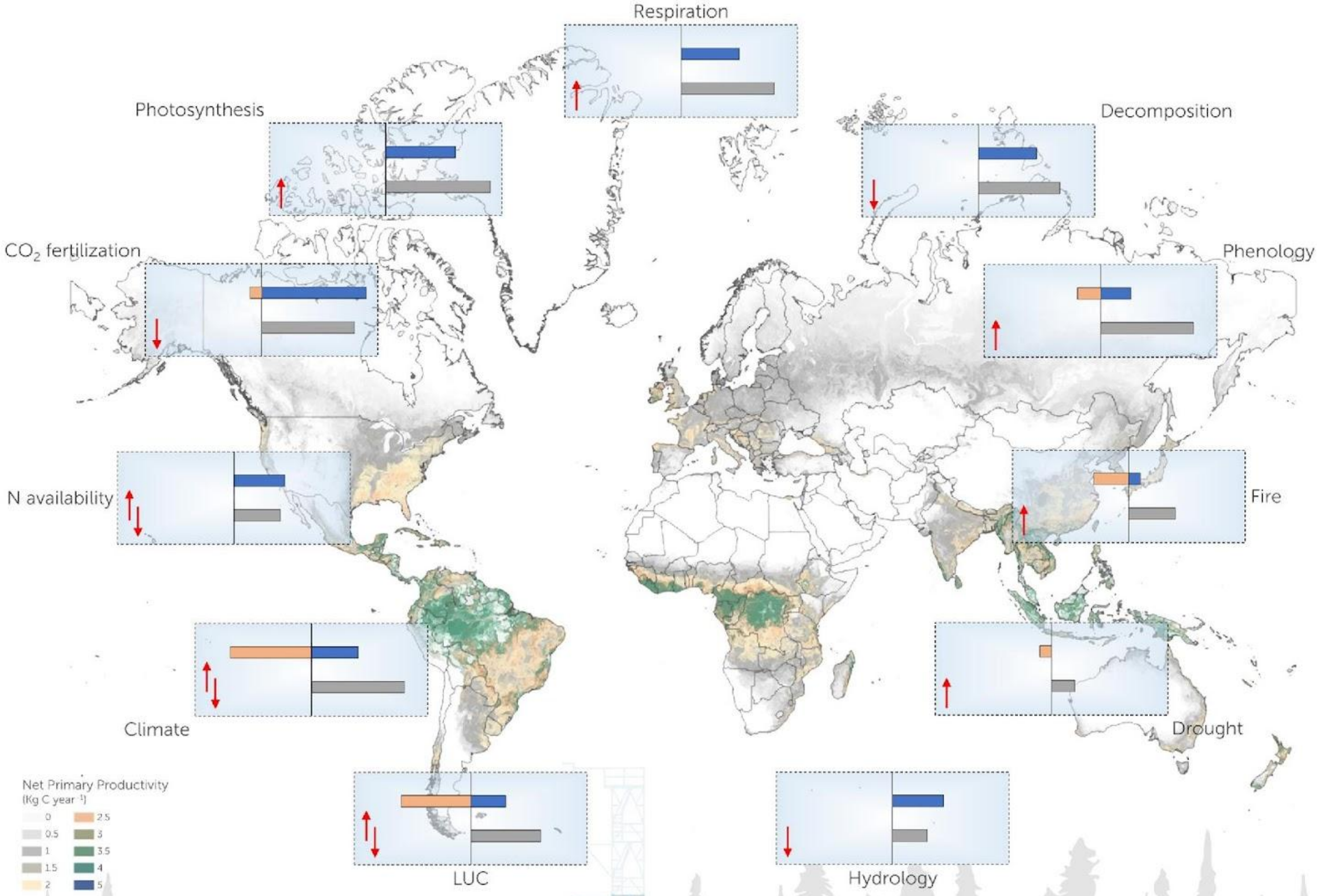
Research on 'C fluxes and AOD'

- Ecosystem exerts positive/negative influence on the vegetation dynamics, contingent on the regional aerosol loading *(Cirino et al. 2014)*.
- Impact of aerosols on primary productivities inferred with the increased (decreased) CO_2 uptake over canopy vegetation *(Li et al. 2020)*.
- Optimal AOD increases diffuse radiation, promoting carbon flux by enhancing terrestrial productivity *(Ezhova et al. 2018)*.
- Questions remain unanswered:



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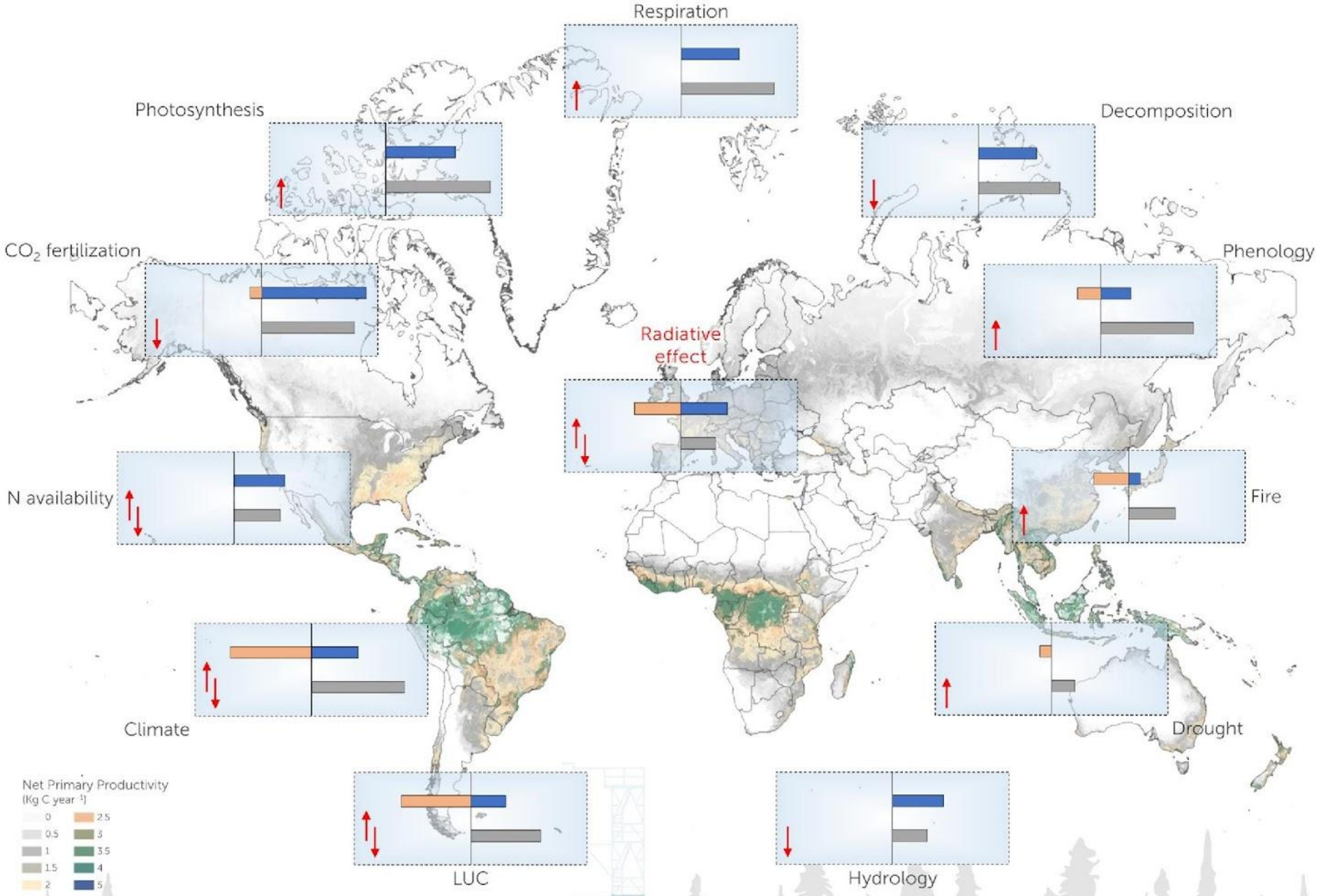
- Questions remain unanswered:
    - **To what degree are the effects on the primary productivity inversed by aerosols (positive to negative or vice versa)?**
    - How are the environmental and biophysical variables altering the ecosystem fluxes, possibly shifting AOD - NPP sensitivity?



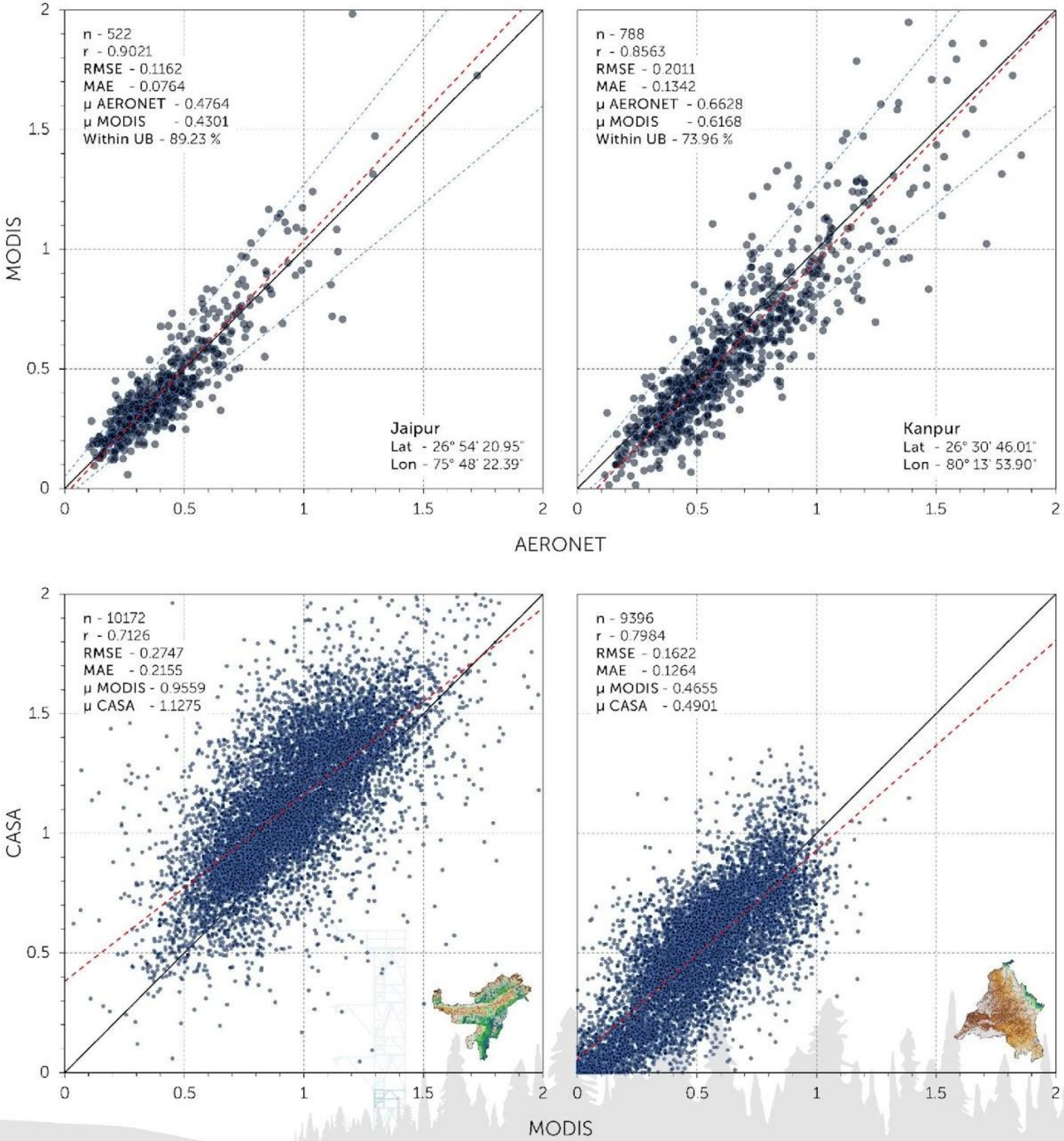
Framework

- CASA

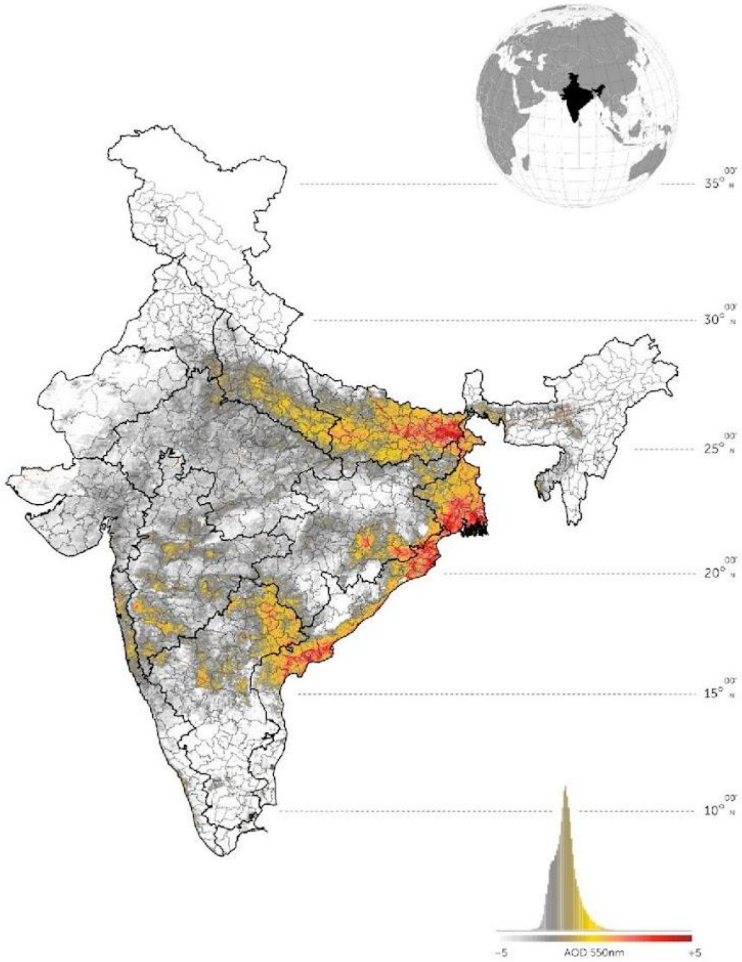
$$NPP\ (x, t) = APAR\ (x, t) \times \varepsilon\ (x, t)$$

- Aerosol data products
  - MODIS level 2 Aerosol Optical Depth (AOD) products at 0.55 µm from 2001–2020.
- SBDART
  - Used to estimate the surface radiation with multiple AOD bins.
  - Monthly PAR_{Diff} and PAR_{Dir} fractions estimated by spatial and temporal averaging.
- Relative sensitivity analysis
  - AOD with 0.1 bins from 0 to 3 was considered for all-sky conditions.
  - Considered y on x regression with NPP being the dependent variable and AOD as the independent variable.
- Innovative trend analysis (ITA)

$$S = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(X_j - Y_i\right)}{\mu}$$



AOD - NPP trend (2001-2020)



- AOD trend was positive with 0.29 $\pm$ 0.09, with a local mean maximum of 0.91 at TGP.
- Spatial distribution of AOD pertains high with minimal fluctuations in its intensity - represent a mirrored C-belt.
- AOD concentration is associated with seasonal cropping patterns and biomass burning.

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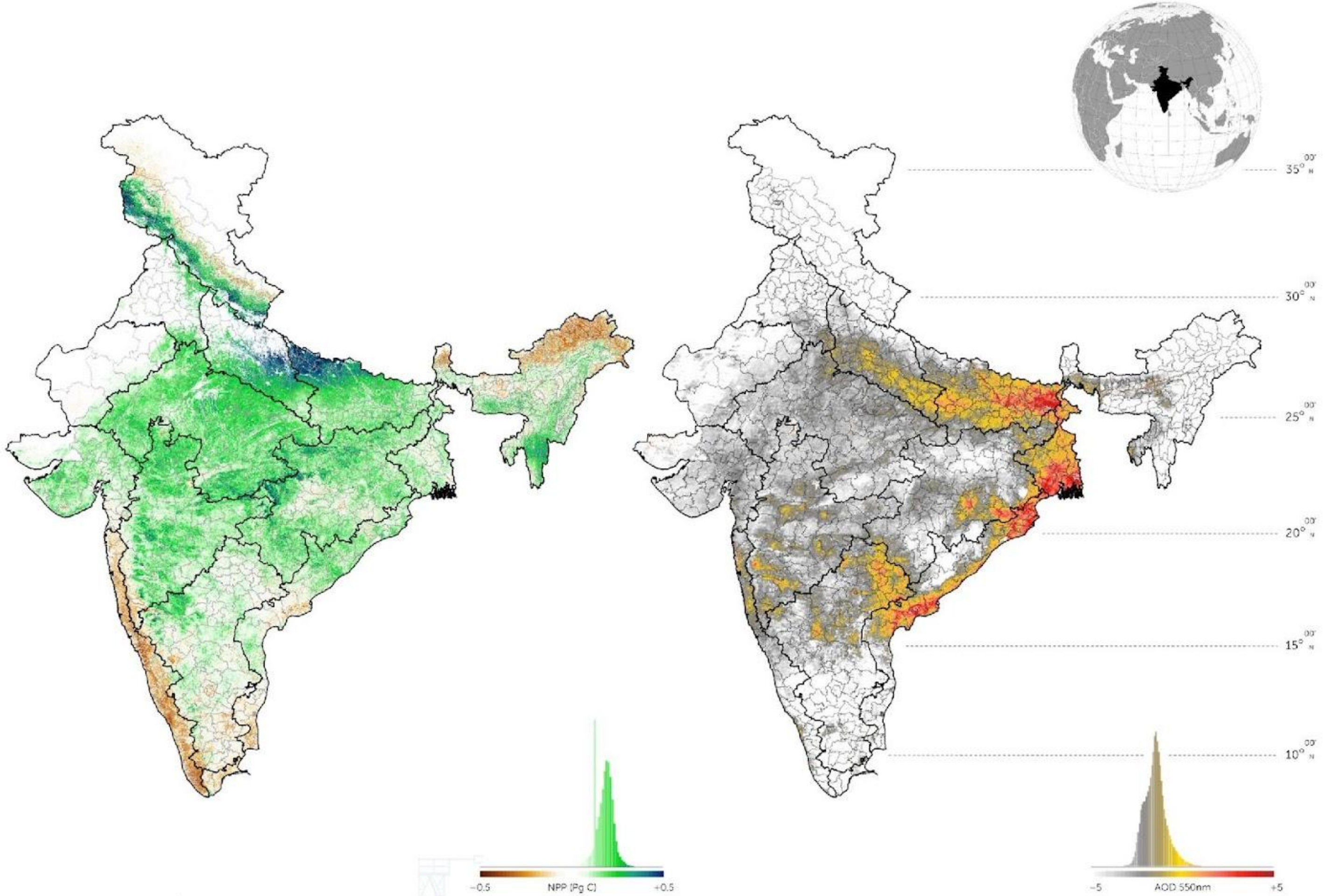

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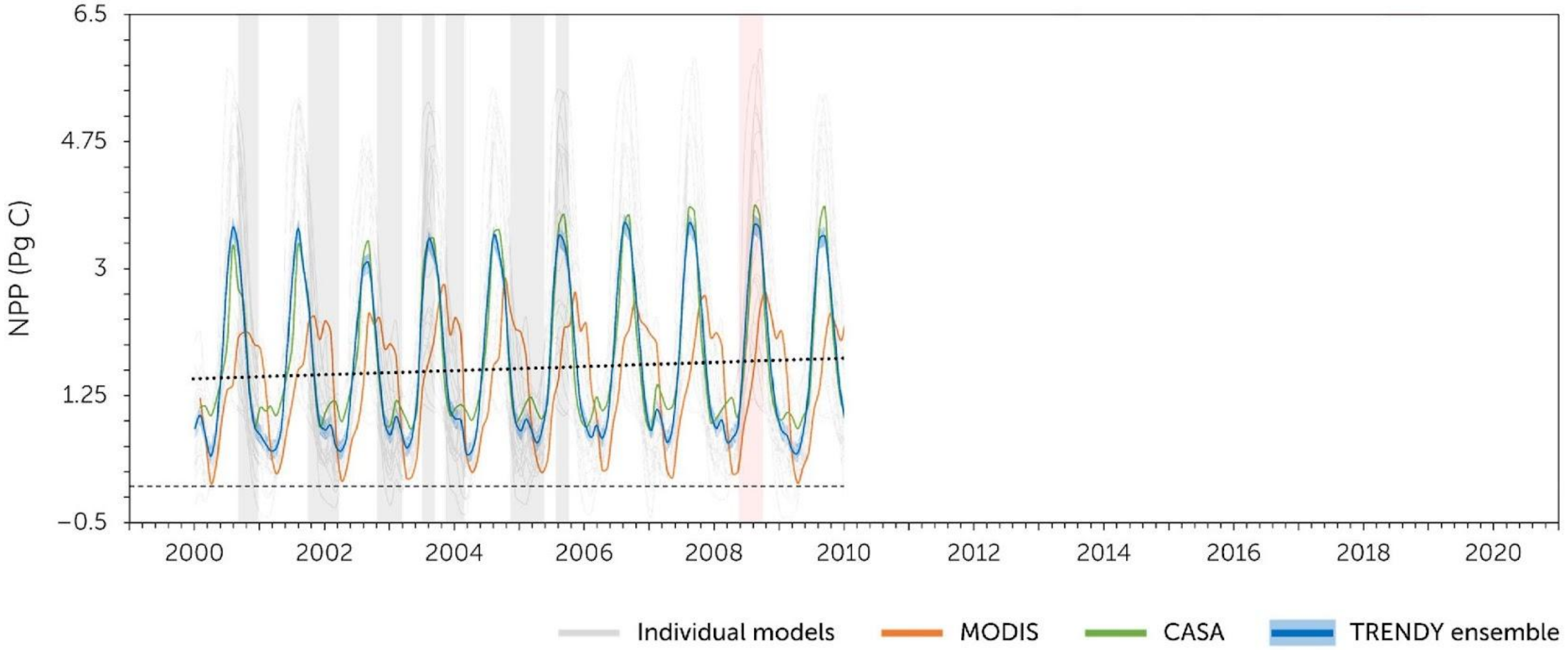
- Spatial distribution of AOD pertains high with minimal fluctuations in its intensity - represent a mirrored C-belt.
- AOD concentration is associated with seasonal cropping patterns and biomass burning.
- Max annual NPP was for the regions with wet climate (0.76 ± 0.14 Pg C $Year^{-1}$); min was with dry climate (0.21 ± 0.06 Pg C $Year^{-1}$).
- Trend with maximum amplitude during the post-monsoon and minimum during the pre-monsoon period.
- EBF zones (EH and WCP), a significant decreasing trend was observed for 5.61%.

Temporal dynamics



- NPP_{CASA} and NPP_{TRENDY} were harmonised in amplitude and annual change, with a difference being 0.03 ± 0.06 Pg C year^{-1}.
- Overall NPP of 1.72 ± 1.21 Pg C year^{-1} with decadal amplitude of 0.11 ± 0.09 Pg C year^{-1}.
- Productivity for 2001-2010 observed an increasing trend of 0.12 ± 0.10 Pg C year^{-1}.

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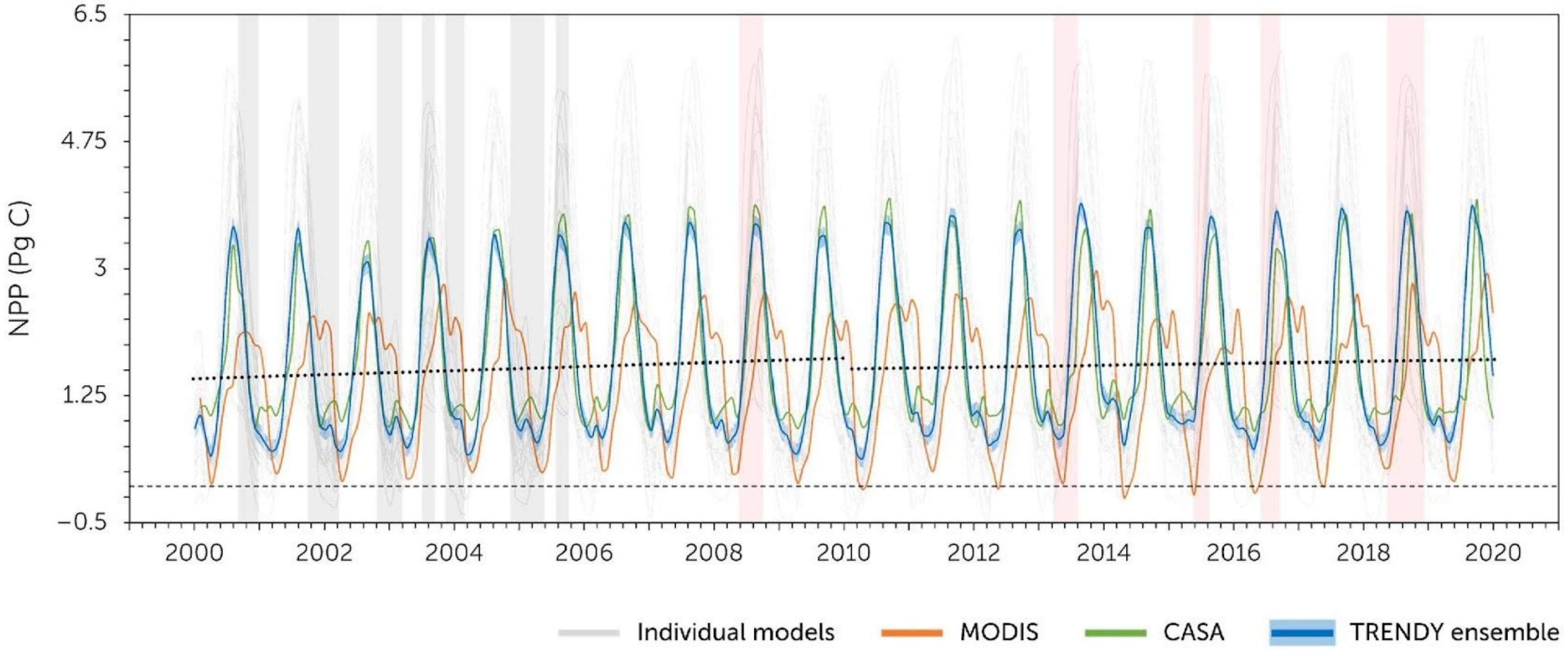

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- Productivity for 2001-2010 observed an increasing trend of 0.12 ± 0.10 Pg C year^{-1}.
- Trend for 2011-2020 declined to 0.10 ± 0.08 Pg C year^{-1}; an overall positive trend with a decline in decadal trend.
- This trend shift was supported by most of the ecological regimes with PFTs of EBF and C3.
- Maximum productivity with the detrended anomalies: 2005, 2012 and 2018; minimum: 2008, 2011, 2013 and 2017.

Decadal and seasonal variability

	Performance	NPP_{TRENDY}		NPP_{CASA}		NPP_{MODIS}		$NPP_{ORCHIDEE}$		NPP_{CLM}	
		D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
Mean	Overall	1.67	1.81	1.74	1.79	1.43	1.46	1.40	1.54	1.04	1.13
	Winter	0.87	0.99	0.99	1.06	1.90	2.08	0.81	0.89	0.54	0.59
	Pre-monsoon	0.66	0.72	1.05	1.03	0.37	0.29	0.57	0.64	0.99	1.11
	Monsoon	2.59	2.72	2.41	2.13	1.13	1.10	2.12	2.27	1.68	1.84
	Post-Monsoon	2.55	2.82	2.49	2.54	2.30	2.35	2.09	2.36	0.93	1.00
Statistics	σ	1.05	1.12	0.95	0.93	0.81	0.89	0.82	0.91	0.50	0.57
	β^*			0.86	0.74	0.32	0.34	0.77	0.80	0.16	0.14
	α^*			0.29	0.33	0.89	0.83	0.11	0.08	0.76	0.89
	d			0.95	0.90	0.41	0.43	0.98	0.98	0.34	0.28
	MAE			0.97	0.93	0.56	0.56	0.95	0.96	0.90	1.03
	RMSE			0.26	0.37	0.90	0.99	0.28	0.28	1.18	1.31

$^*\rho < 0.05$

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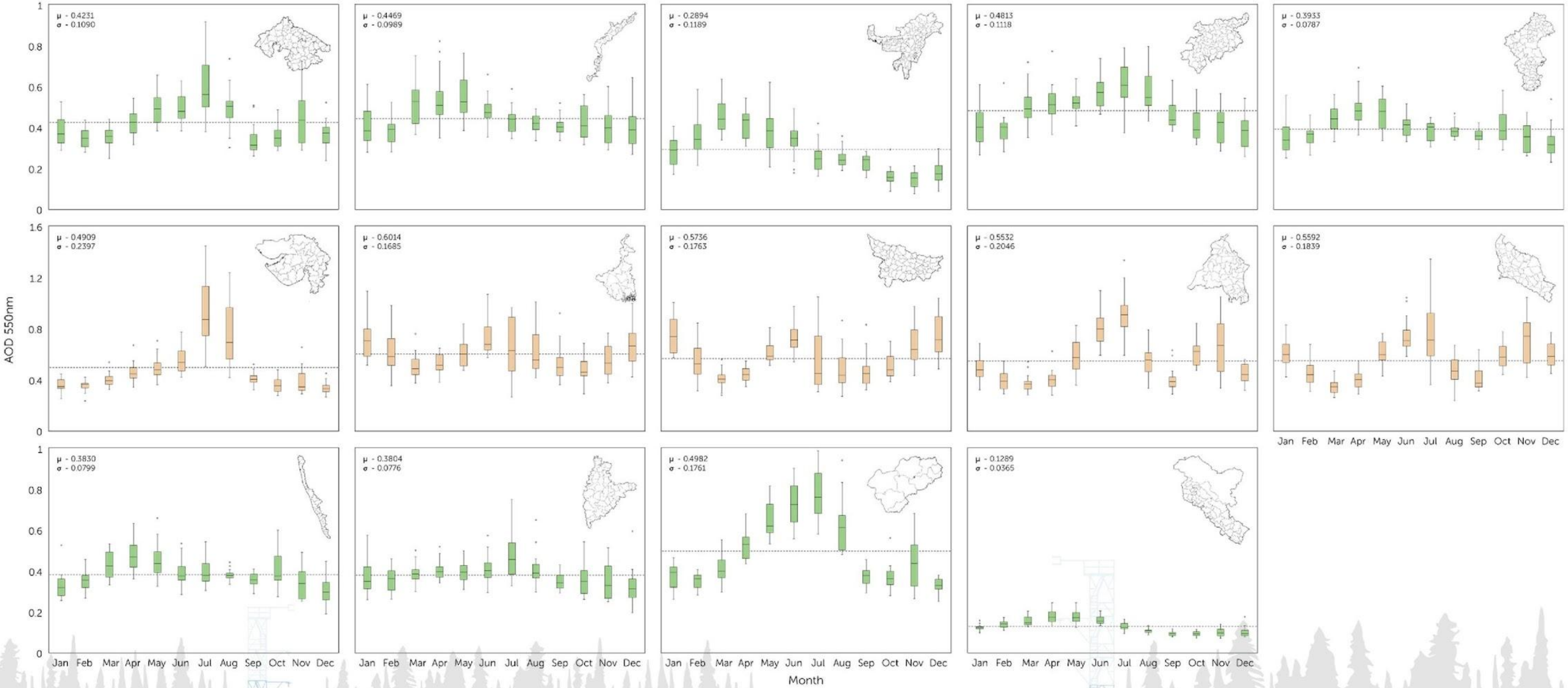
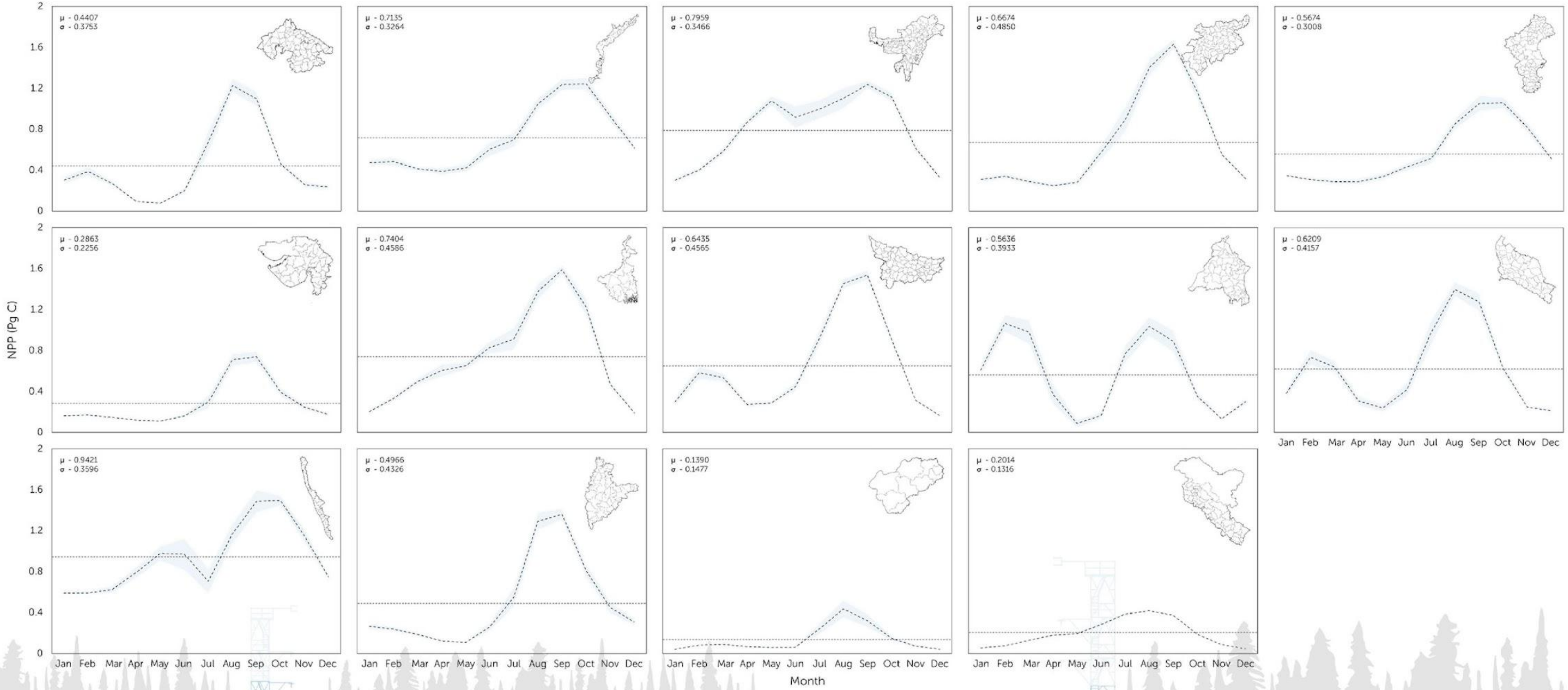
AOD variability across ecosystems



NPP variability across ecosystems



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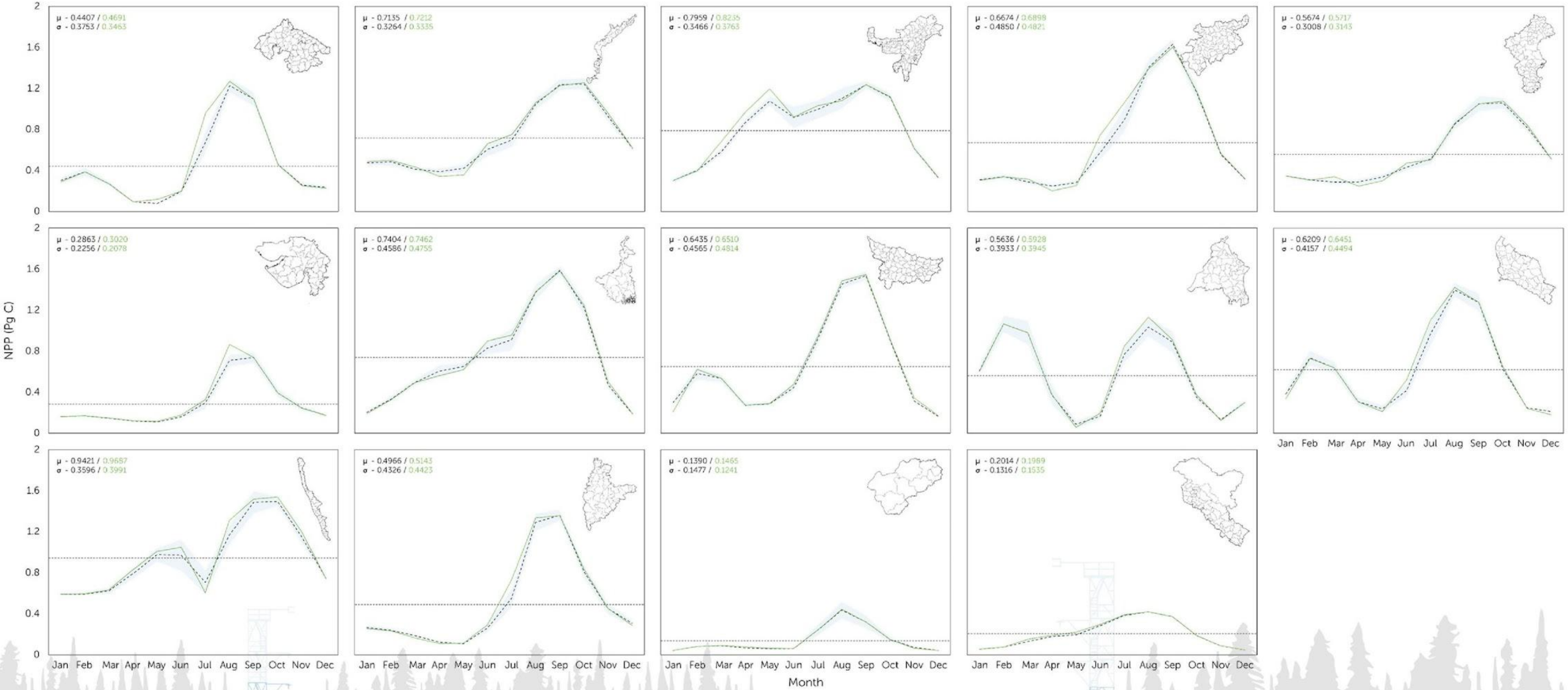

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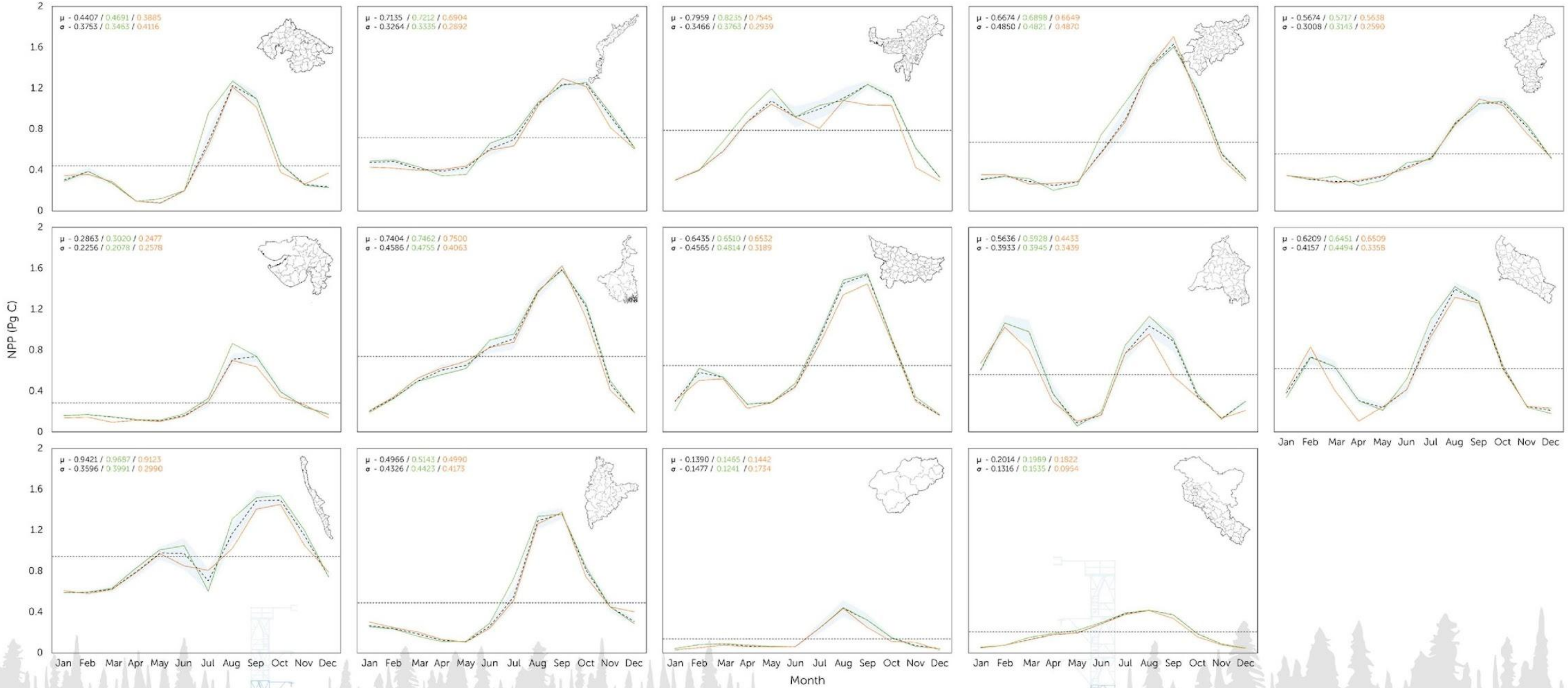
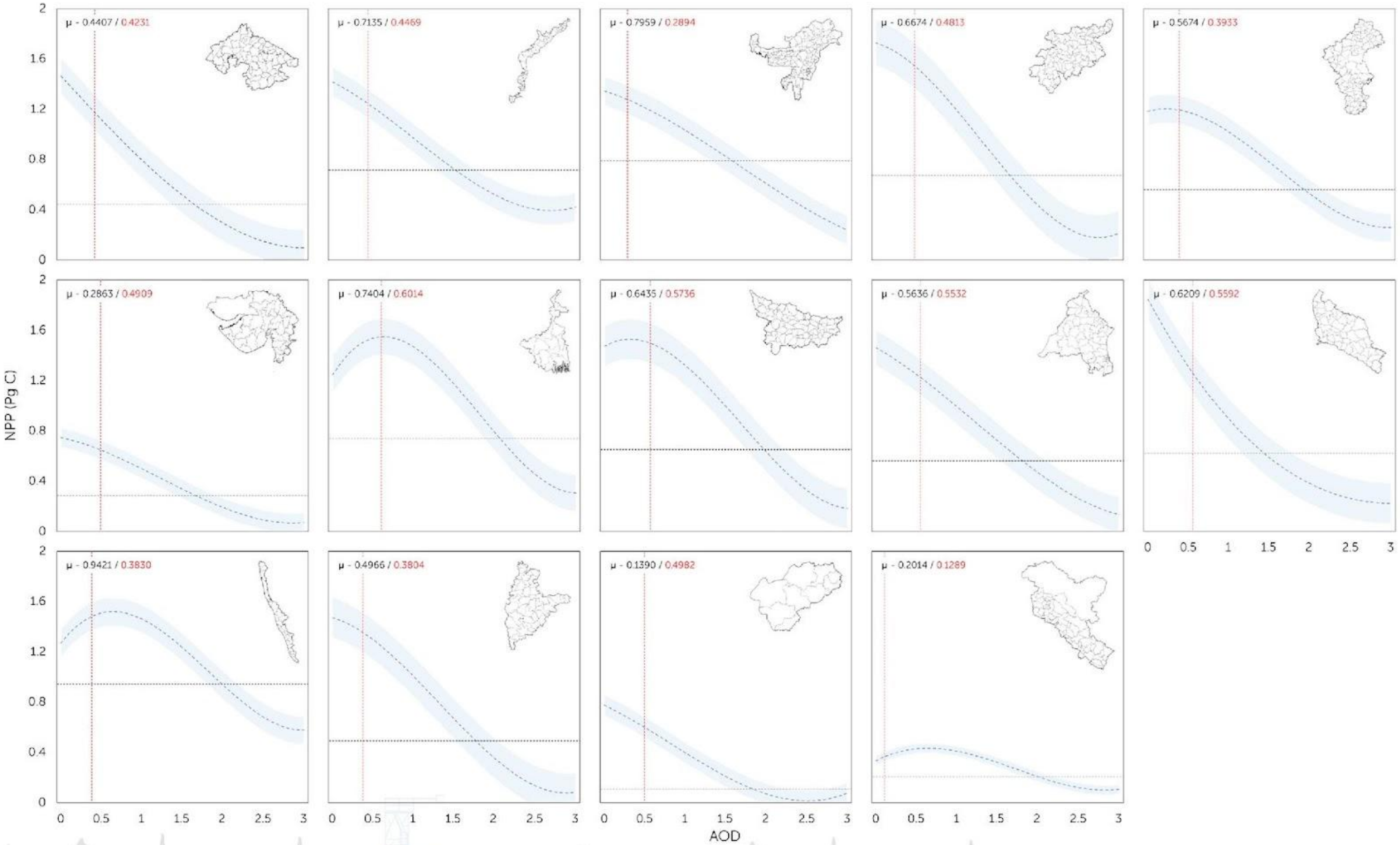


AOD - NPP sensitivity



- AOD was inversely proportional to NPP - exhibited considerable impact when exceeds the optimal threshold.
- Agroecosystems had maximum NPP with higher AOD – the fertilization effects were lower due to the consistent, intense AOD load.
- Vegetational adaptiveness in the agroecosystems to aerosols was stronger than in forest-based.

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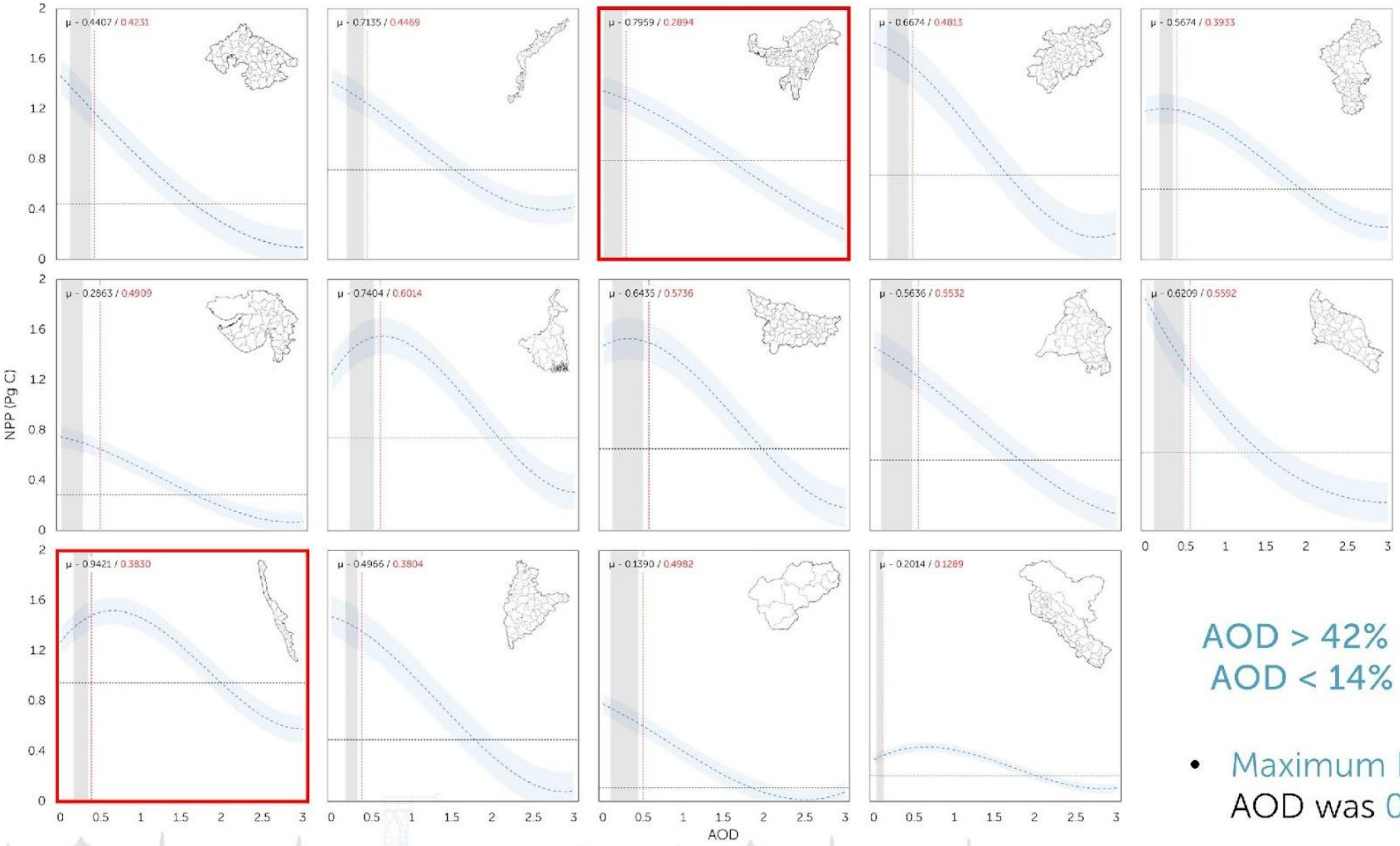

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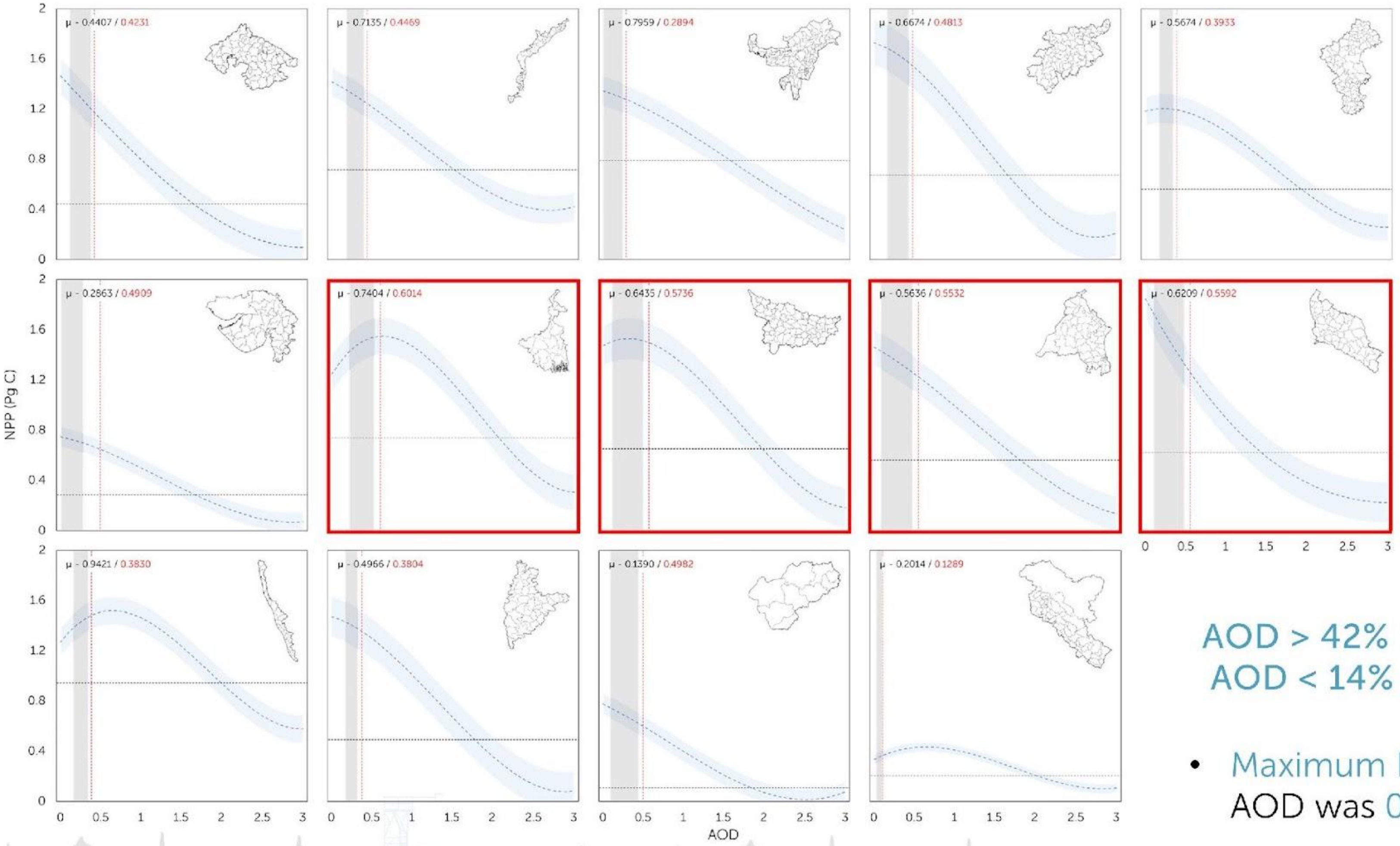

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- Agroecosystem's NPP growth was restricted by 0.59, with the maximum growth was observed at 0.49.

AOD - NPP

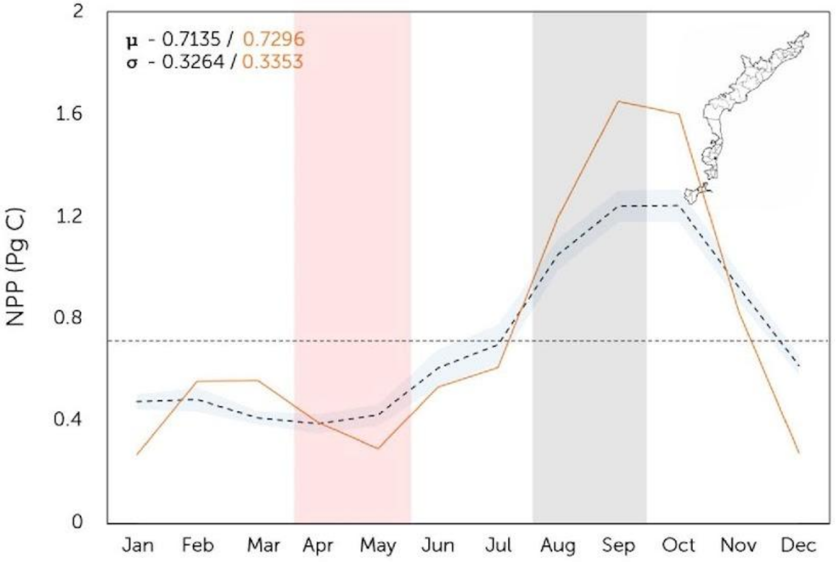
Agroecological zones	$\mu \pm \sigma$			S
	NPP	NPP_S	AOD	NPP_S
CPlat	0.4407 ± 0.37	0.4610 ± 0.38	0.4231 ± 0.10	0.0003
ECP	0.7135 ± 0.32	0.7296 ± 0.33	0.4469 ± 0.09	0.0000*
EH	0.7959 ± 0.34	0.8187 ± 0.38	0.2894 ± 0.12	−0.0003**
EPlat	0.6674 ± 0.48	0.6027 ± 0.42	0.4813 ± 0.11	0.0001***
GP	0.2863 ± 0.22	0.3421 ± 0.18	0.4909 ± 0.24	0.0002**
LGP	0.7404 ± 0.45	0.7190 ± 0.30	0.6014 ± 0.17	−0.0004
MGP	0.6435 ± 0.45	0.6057 ± 0.27	0.5736 ± 0.18	−0.0003***
SPlat	0.5674 ± 0.30	0.5527 ± 0.28	0.3933 ± 0.08	−0.0001**
TGP	0.5636 ± 0.39	0.5601 ± 0.35	0.5532 ± 0.21	0.0002**
UGP	0.6209 ± 0.41	0.6019 ± 0.39	0.5592 ± 0.18	0.0000*
WCP	0.9421 ± 0.36	0.9482 ± 0.37	0.3830 ± 0.08	−0.0004*
WH	0.2014 ± 0.13	0.1981 ± 0.13	0.1289 ± 0.03	0.0001*
WP	0.1390 ± 0.14	0.1421 ± 0.18	0.4982 ± 0.17	0.0002
WPlat	0.4966 ± 0.43	0.3797 ± 0.37	0.3804 ± 0.07	−0.0003**

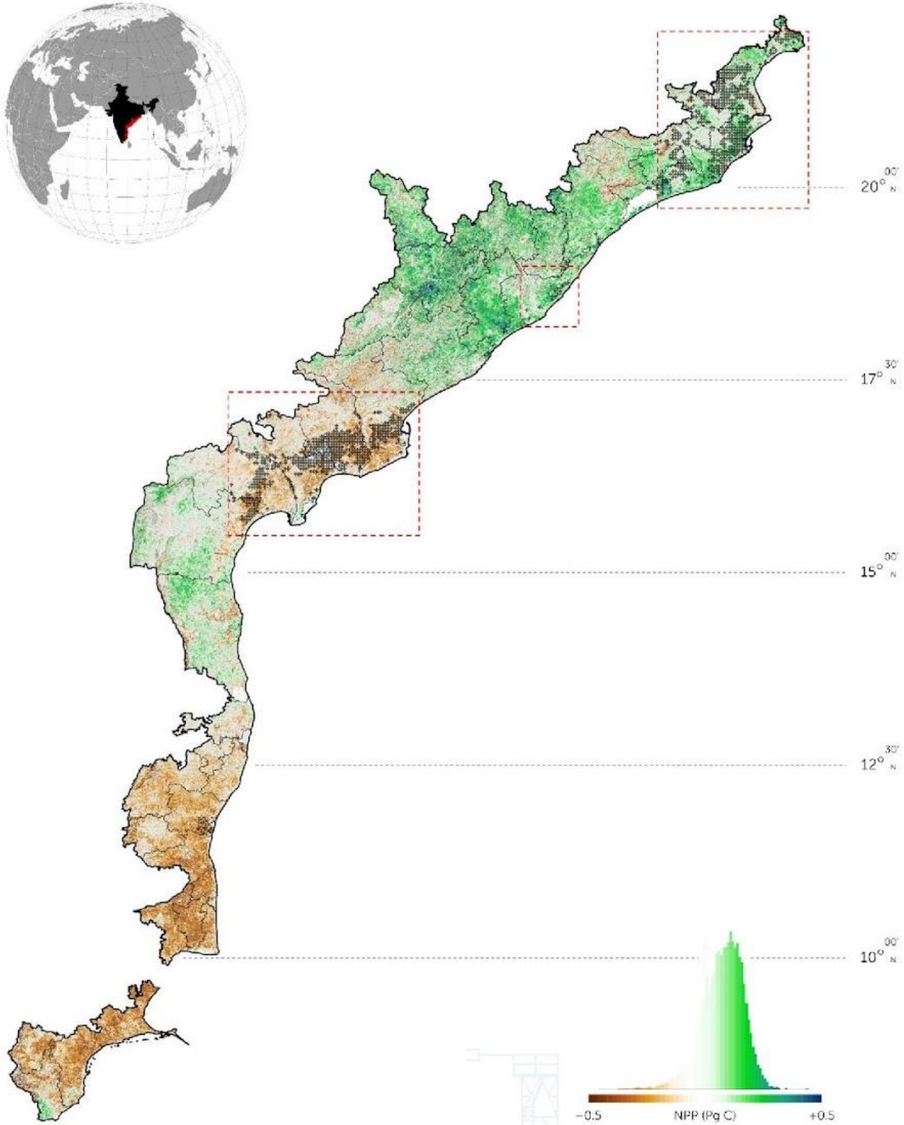
*$\rho < 0.05$; **$\rho < 0.01$; ***$\rho < 0.001$

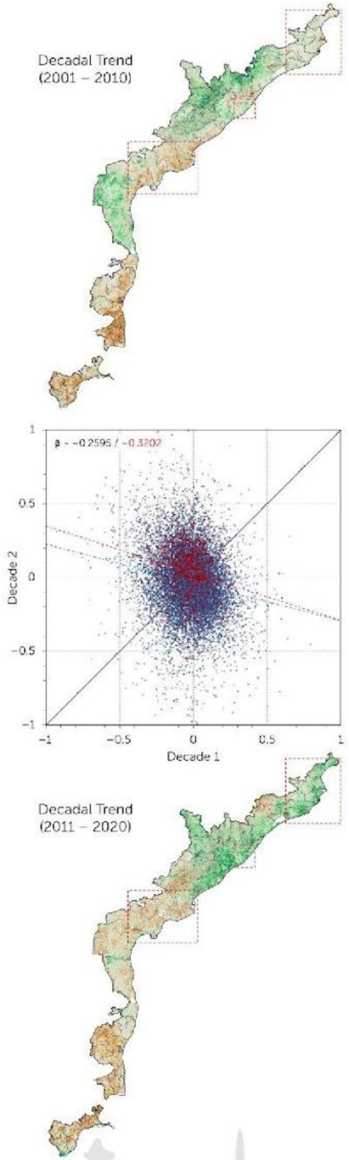
- Zones with permanent vegetation cover, sensitivity was increased between NPP for higher AOD.
- Possibly induced due to the structural complexity of the canopy over the regions (ECP).
- AOD positively influenced the canopy scale photosynthesis by diffuse radiation and promoted NPP but less likely to crop canopy (MGP).
- Other than agro regions, seasonal AOD concentrations influenced NPP in the ecosystems.
- Higher concertation of AOD nullified the effect and was non-significant for all vegetation-structure canopy (GP).
- The impeding effect of AOD across the agroecological zones of LGP, MGP, TGP, and UGP altered the overall NPP by 11%.

Maximum negative effect: WPlat and EPlat
Maximum enhancement: EH, ECP, and SPlat

Sensitivity across ECP







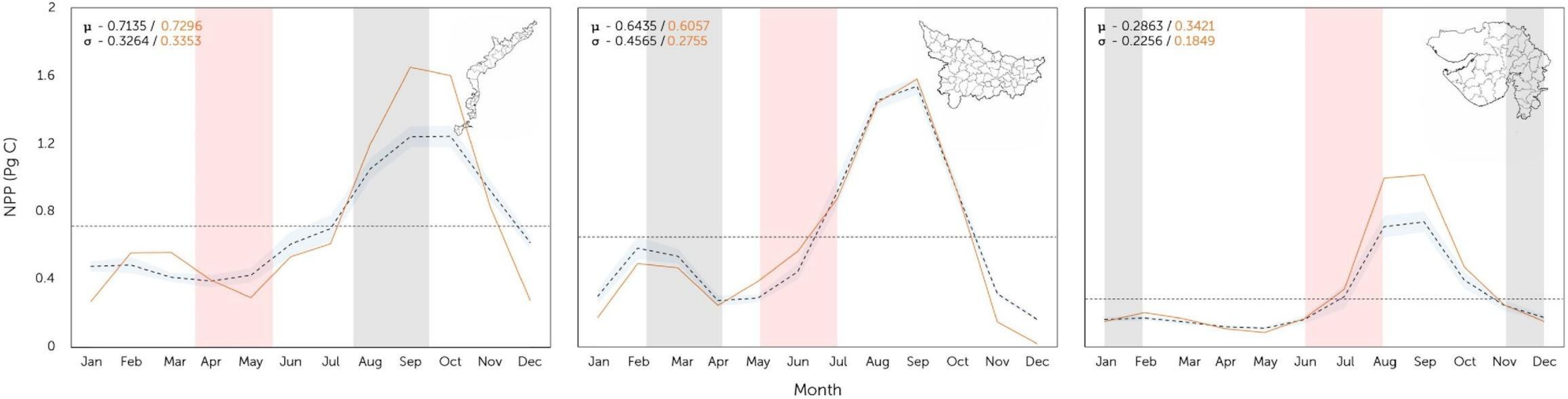
- A non-homogenous response in the spatial sensitivity and temporal trend.

Optimal AOD = maximum NPP in **post-monsoon**
High AOD = maximum NPP drop in **pre-monsoon**

- ECP represented a declining spatial trend in NPP; but the zones with optimal AOD, induced greenness.

- Presumably, anthropogenic interventions in cropland management may have also steered the sensitivity responses of NPP.

Sensitivity across selected zones



- Optimal AOD across the canopy-based ecosystems induce ecosystem productivity in diffuse conditions rather than the clear-sky condition.
- When AOD load was beyond the optimum the radiation is cast to reach the canopy and is expected to decrease the canopy radiative propagation and inverse the condition.
- Zones with complex vegetation canopy, NPP increases with high aerosol conditions as the diffuse radiation might have enhanced the photosynthetic process of the shaded non-sunlit leaves.

Summary and caveats

- IAV and seasonal trend variability
  - Agroecological ecosystems played dominant role in the seasonal trend and the tropical forests poised the overall trend.
  - Exhibited a sensible increment in most of the ecological zones, with an overall increasing trend but not in decadal.
  - Productivity peak was in post-monsoon owing to the response of phenology and decreased during pre-monsoon.
- Feedback/Sensitivity
  - AOD had a heterogeneous response to the NPP trend due to the canopy architecture, prodigiously in the forest ecosystems than the agroecosystems.
  - NPP sensitivity to AOD is dynamic by the radiation pathway and the canopy structure.

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  - NPP sensitivity to AOD is dynamic by the radiation pathway and the canopy structure.
- Caveats
  - Considered the aerosol effects by governing the biophysical parameters, as AOD interactions with climatic parameters are limited to derive a consistent conclusion.
  - Time-dependent mono scenario study only highlights the region's NPP, sensitive to AOD.
  - Inconsistent significance in the sensitivity trend, due to the spatial averaging of multiple pixels that might have different phenological and canopy structures with different radiation intensities.

Thank you

References

- Cirino, G.G.; Souza, R.A.F.; Adams, D.K.; Artaxo, P. The effect of atmospheric aerosol particles and clouds on net ecosystem exchange in the Amazon. Atmos. Chem. Phys. **2014**, 14, 6523–6543.
- Ezhova, E.; Ylivinkka, I.; Kuusk, J.; Komsaare, K.; Vana, M.; Krasnova, A.; Noe, S.; Arshinov, M.; Belan, B.; Park, S.-B.; et al. Direct effect of aerosols on solar radiation and gross primary production in boreal and hemiboreal forests. Atmos. Chem. Phys. **2018**, 18, 17863–17881.
- Jay, S.; Potter, C.; Crabtree, R.; Genovese, V.; Weiss, D.J.; Kraft, M. Evaluation of modelled net primary production using MODIS and LANDSAT satellite data fusion. Carbon Balance Manag. **2016**, 11, 8.
- Ji, L.; Peters, A.J. Performance evaluation of spectral vegetation indices using a statistical sensitivity function. Remote Sens. Environ. **2007**, 106, 59–65.
- Li, X.; Liang, H.; Cheng, W. Spatio-temporal variation in AOD and correlation analysis with PAR and NPP in China from 2001 to 2017. Remote Sens. **2020**, 12, 976.
- Petroff, A.; Mailliat, A.; Amielh, M.; Anselmet, F. Aerosol dry deposition on vegetative canopies. Part I: Review of present knowledge. Atmos. Environ. **2008**, 42, 3625–3653.
- Potter, C.S.; Randerson, J.T.; Field, C.B.; Matson, P.A.; Vitousek, P.M.; Mooney, H.A.; Klooster, S.A. Terrestrial ecosystem production: A process model based on global satellite and surface data. Glob. Biogeochem. Cycles **1993**, 7, 811–841.
- Ricchiazzi, P.; Yang, S.; Gautier, C.; Sowle, D. SBDART: A research and teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere. Bull. Am. Meteorol. Soc. **1998**, 79, 2101–2114.
- Spitters, C.J.T. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis Part II. Calculation of canopy photosynthesis. Agric. For. Meteorol. **1986**, 38, 231–242.
- Strada, S.; Unger, N.; Yue, X. Observed aerosol-induced radiative effect on plant productivity in the eastern United States. Atmos. Environ. **2015**, 122, 463–476.
- Vicent, J.; Sabater, N.; Verrelst, J.; Alonso, L.; Moreno, J. Assessment of approximations in aerosol optical properties and vertical distribution into FLEX atmospherically-corrected surface reflectance and retrieved sun-induced fluorescence. Remote Sens. **2017**, 9, 675.
- Zhang, Y.; Hu, Q.; Zou, F. Spatio-temporal changes of vegetation net primary productivity and its driving factors on the Qinghai-Tibetan plateau from 2001 to 2017. Remote Sens. **2021**, 13, 1566.