BioSpace25 - Biodiversity insight from Space
10 - 14 February 2025 | ESA-ESRIN | Frascati - Italy

Quantifying the relationship between forest structural diversity and forest resilience

Agata Elia[1], Mark Pickering[2], Marco Girardello[3], Giovanni Forzieri[4], Gonzalo Oton[3], Matteo Piccardo[2], Guido Ceccherini[3], Mirco Migliavacca[3], Alessandro Cescatti[3]

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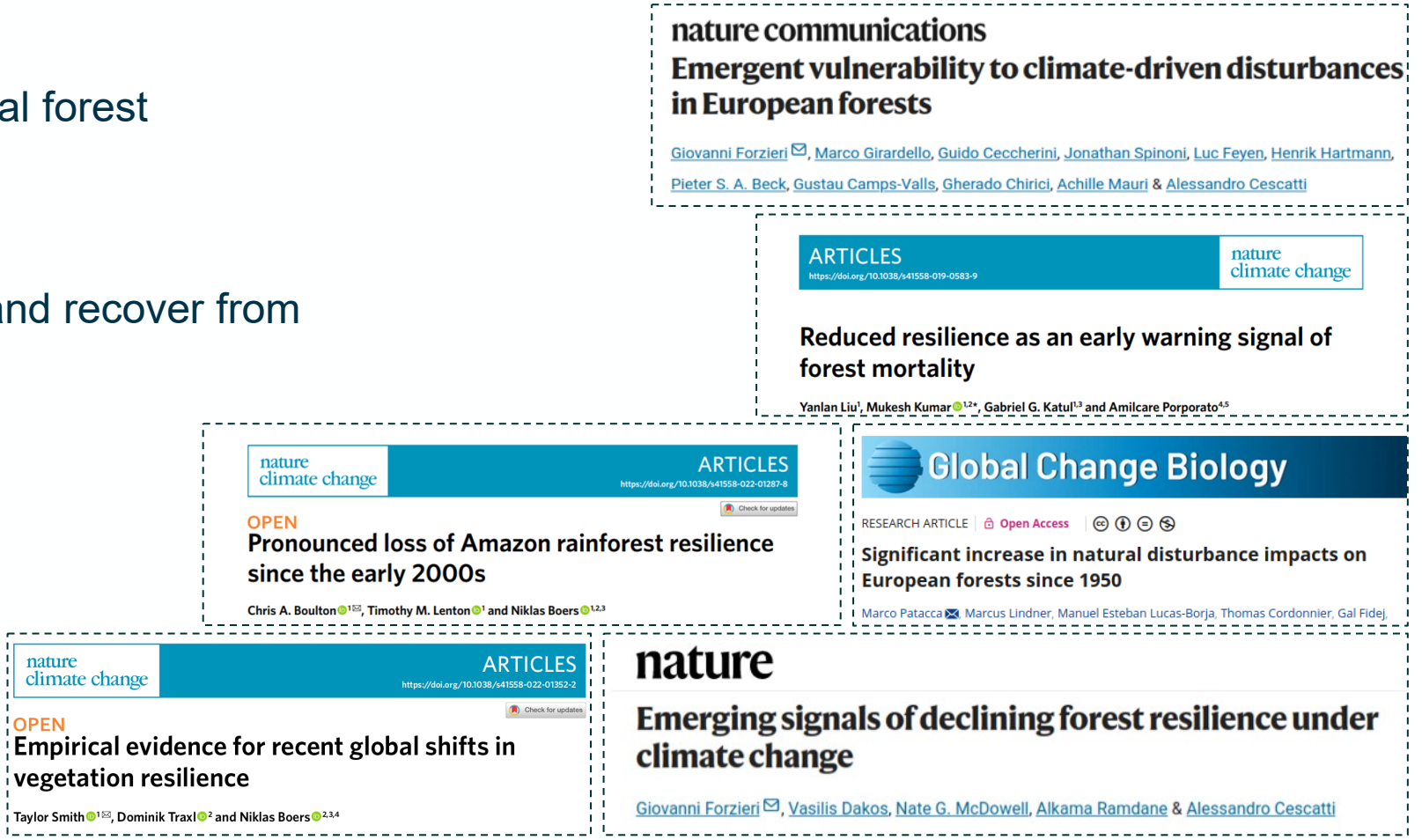
Quantifying the relationship between forest structural diversity and forest resilience

Forest resilience is declining

- Increasing evidence of declining global forest resilience under climate change
- Resilience is the ability to withstand and recover from perturbations/disturbances
- What makes a forest more resilient?



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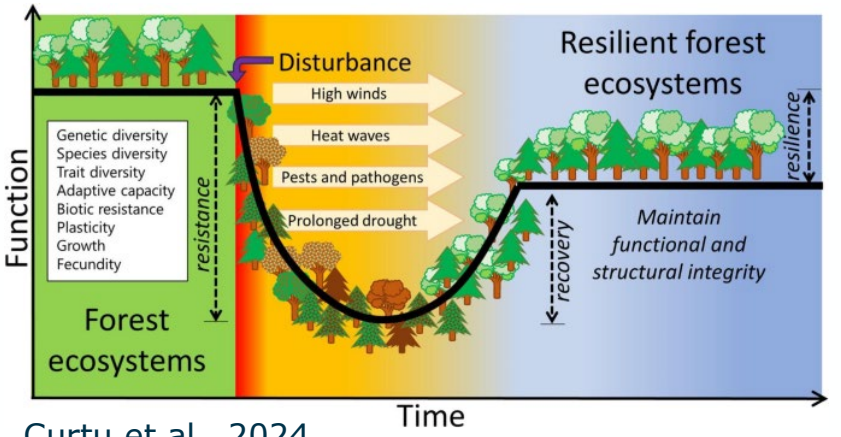
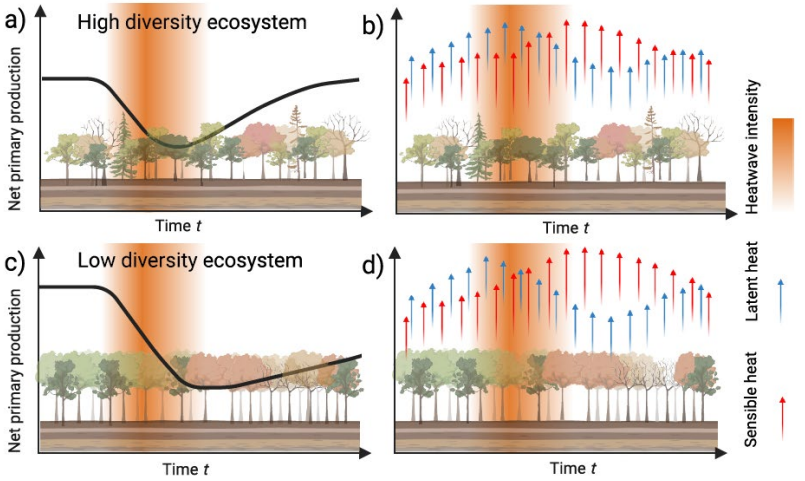
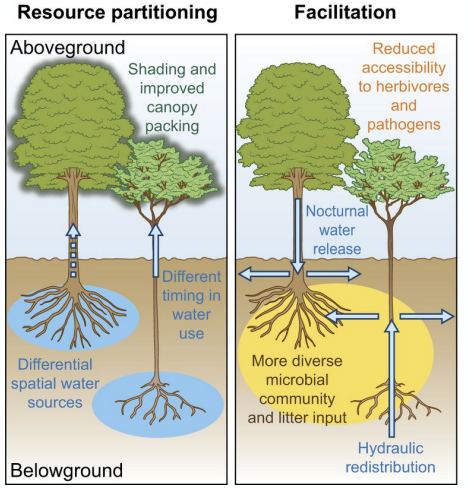
Diverse forests are more resilient



Curtu et al., 2024



Mahecha et al., 2024



Grossiord, 2018

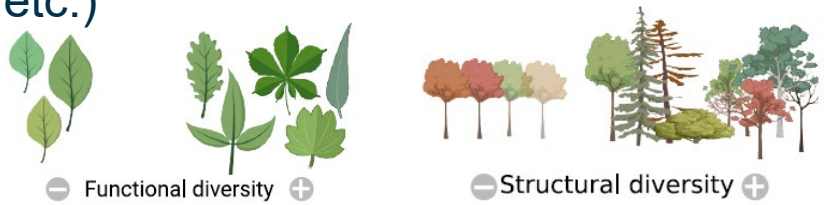
Quantifying the relationship between forest structural diversity and forest resilience

Forest resilience is declining

- Increasing evidence of declining global forest resilience under climate change
- What makes a forest more resilient?

Diverse forests are more resilient

- Studies confirmed the role of forest diversity in promoting forest resilience, mostly at local scales and mechanism/species/disturbance specific
- Forest Structural Diversity (FSD) is a measure of variability within the canopy structure connected to functional diversity (species, age, leaf, stem and root traits, etc.)



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Quantifying the relationship between forest structural diversity and forest resilience

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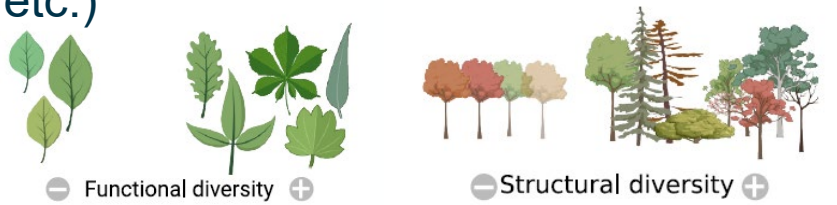

Mahecha et al., 2024

- **FSD can be controlled by forest management!**

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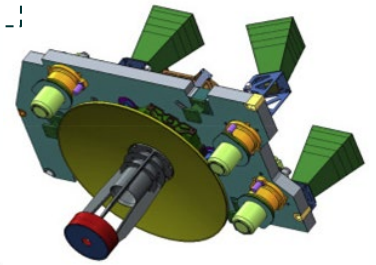
Forest Structural Diversity (FSD)

A dataset on the structural diversity of European forests

Marco Girardello, Gonzalo Oton, Matteo Piccardo, Mark Pickering, Agata Elia, Guido Ceccherini, Mariano Garcia, Mirco Migliavacca, and Alessandro Cescatti

Preprint in ESSD!



Three FSD metrics derived from GEDI (LIDAR):

- **Horizontal (FSDH)**: variability in canopy height

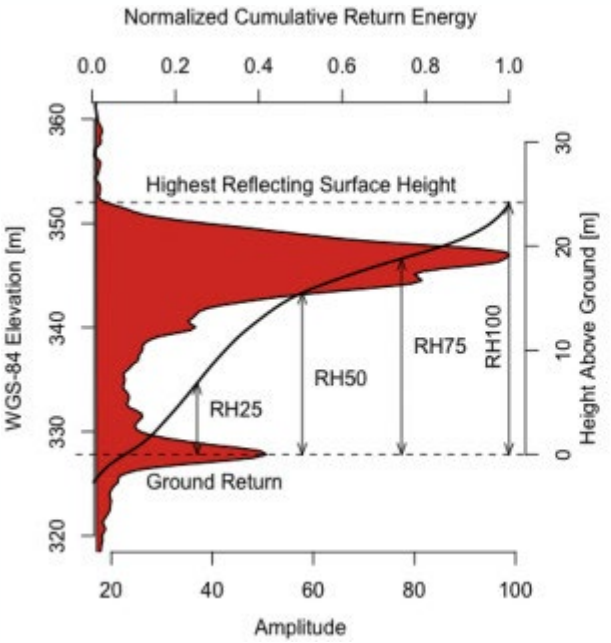
$$\text{S.D. in RH98} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(RH98_i - \mu(RH98) \right)^2}$$

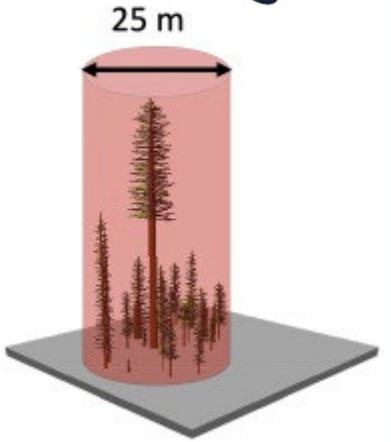
- **Vertical (FSDV)**: evenness in the vertical vegetation distribution

$$\text{Excess kurtosis} = \frac{E[(X-\mu(X))^4]}{(E[(X-\mu(X))^2])^2} - 3$$

- **Combined Horizontal & Vertical (FSDH+V)**: variability and complexity in canopy layers

$$\text{Shannon Entropy} = -\sum_i p_i \, log(p_i)$$



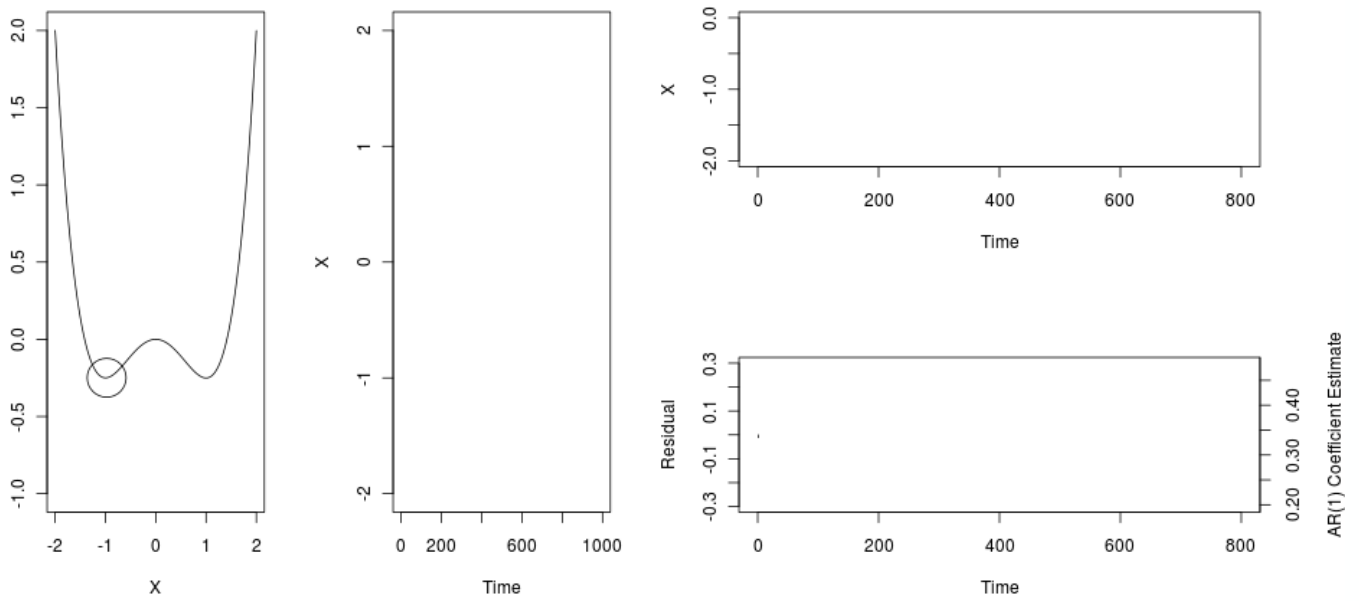


→ The higher the metric, the higher the FSD

Quantifying the relationship between forest structural diversity and forest resilience

Resilience

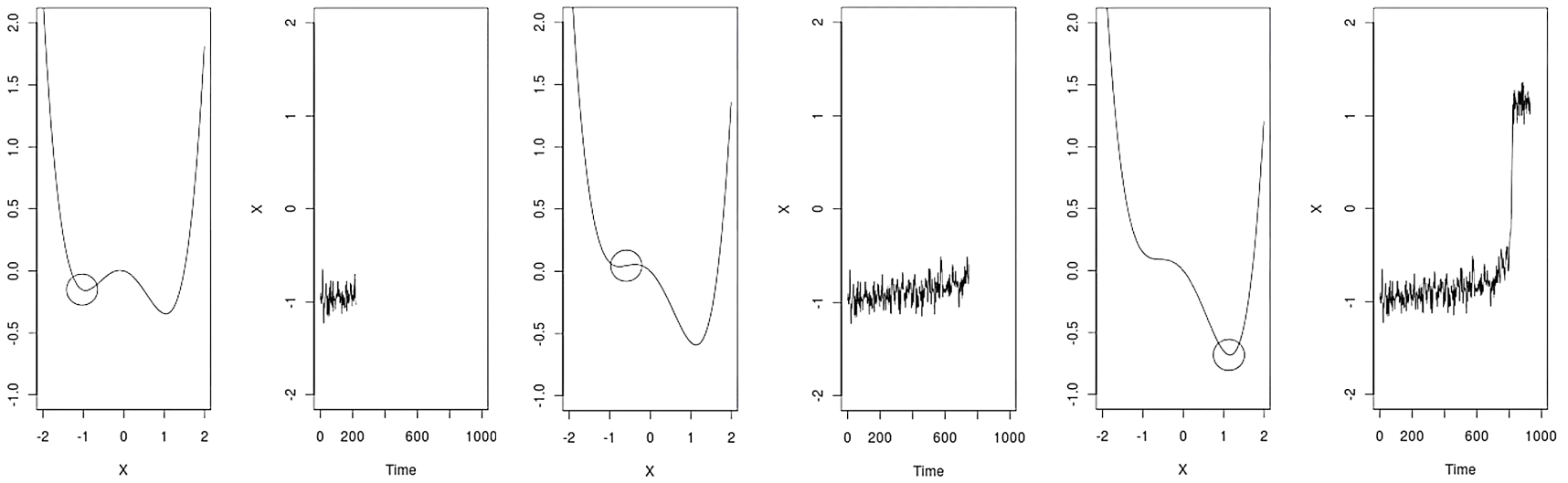
- Forests constantly undergo small perturbations, we can use this information to predict response to big disturbances and regime shifts
- Engineering resilience, the rate at which a system returns from small displacements about the equilibria
- Systems approaching bifurcation point exhibit critical slowing down (CSD)



C. Boulton, University of Exeter (UK)

Quantifying the relationship between forest structural diversity and forest resilience

Resilience



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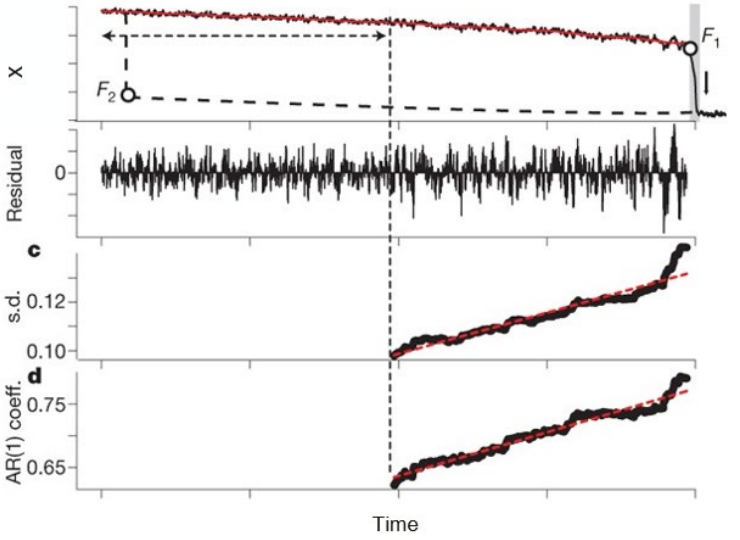


Adapted from Sugihara et al., 2009

Quantifying the relationship between forest structural diversity and forest resilience

Resilience

Two resilience metrics from CSD theory:

- **AC1 based restoration rate (ecosystem memory):**

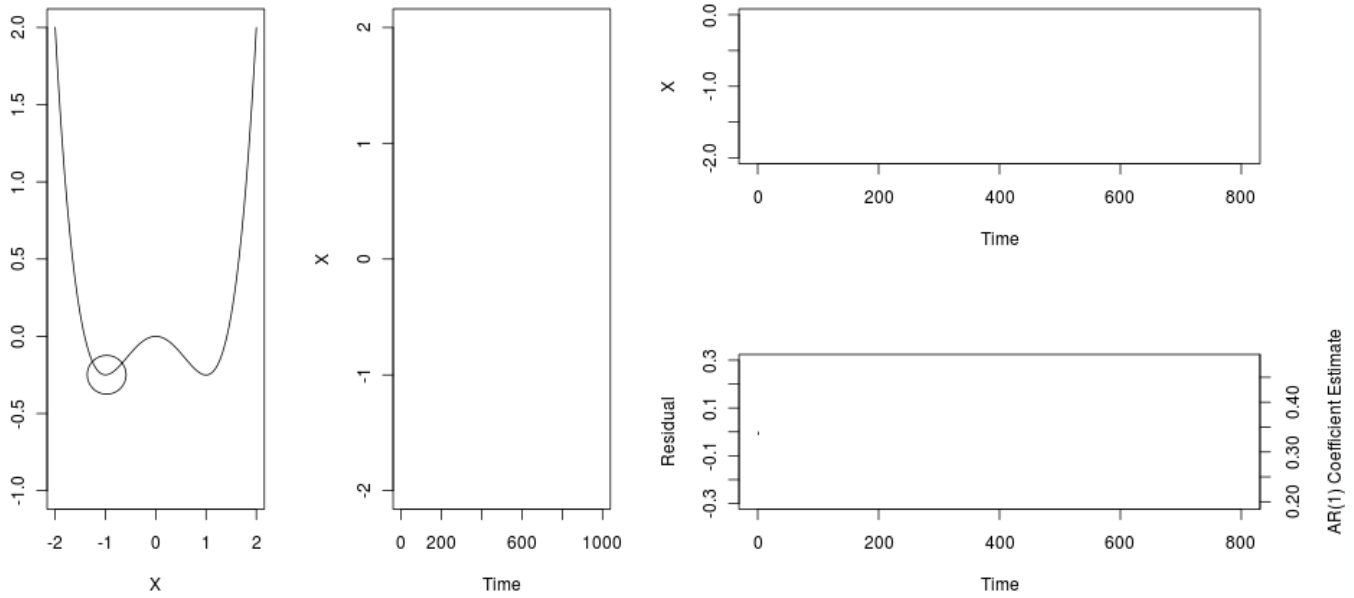
$$\text{Rest. Rate AC1} = |\ln(\alpha)|$$

where α is 1-lag autocorrelation

- **Variance based restoration rate (ecosystem stability):**

$$\text{Rest. Rate Variance} = \left|\frac{1}{2}\ln\left(1-\frac{\sigma^2}{V[x]}\right)\right|$$

where V is the variance and σ is a noise term



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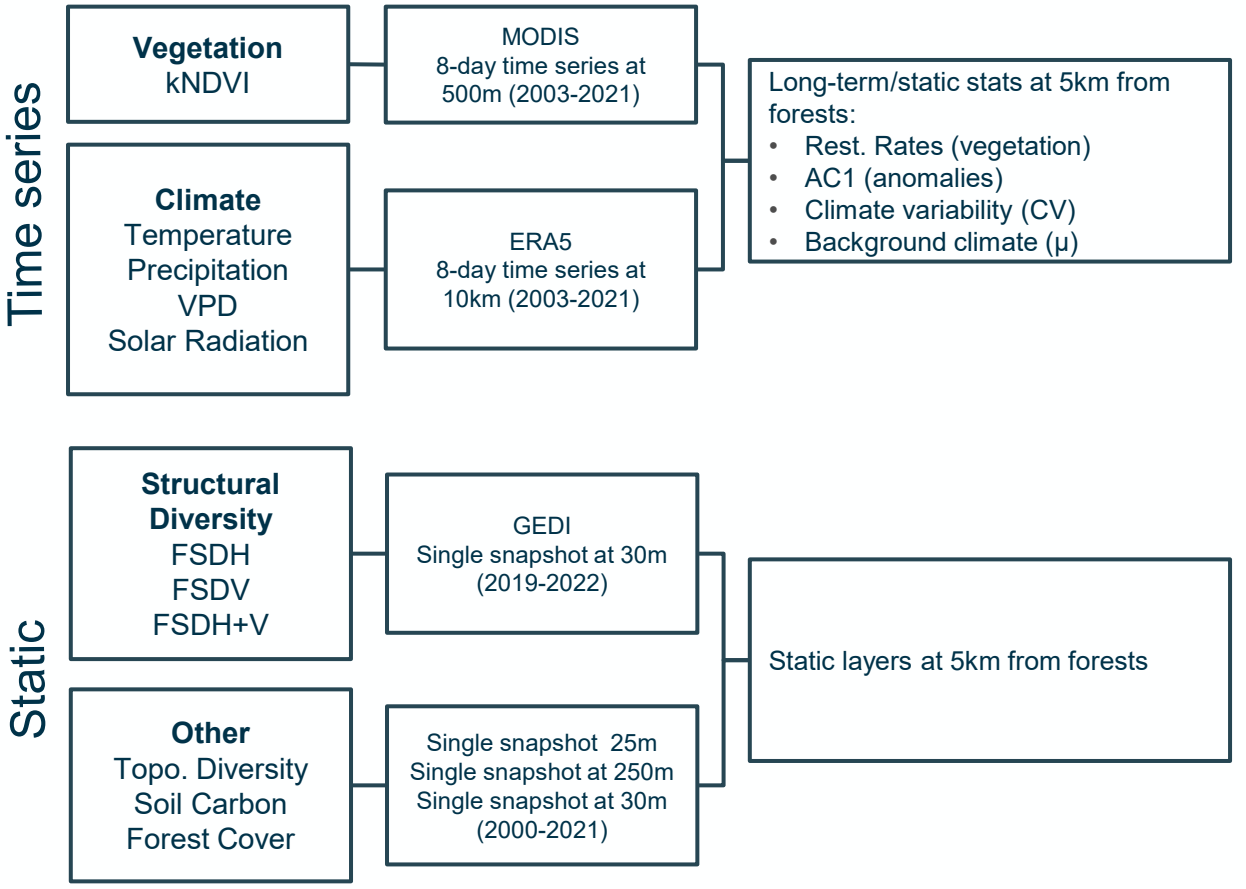
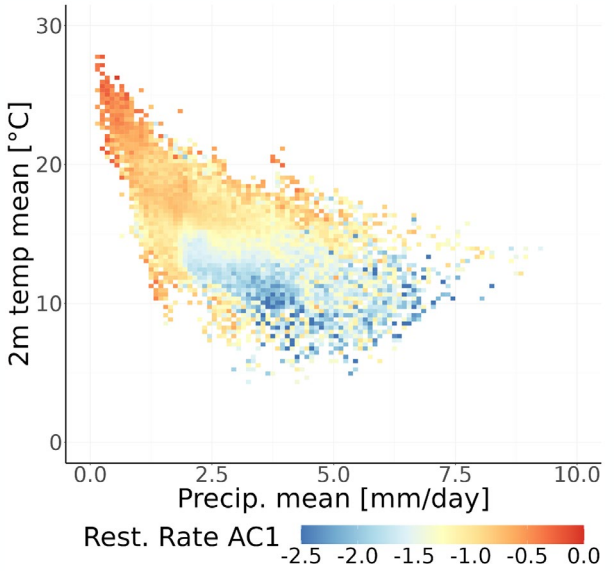
→ The higher the Rest. Rate, the higher the resilience

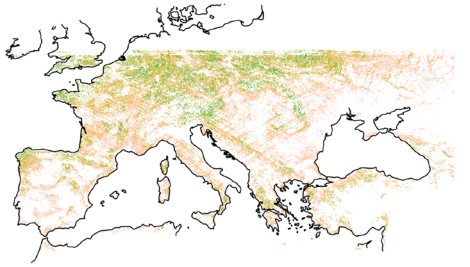
Quantifying the relationship between forest structural diversity and forest resilience

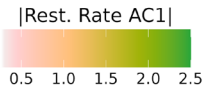
Methodology

Extract the FSD - resilience relationship while controlling for confounding environmental factors









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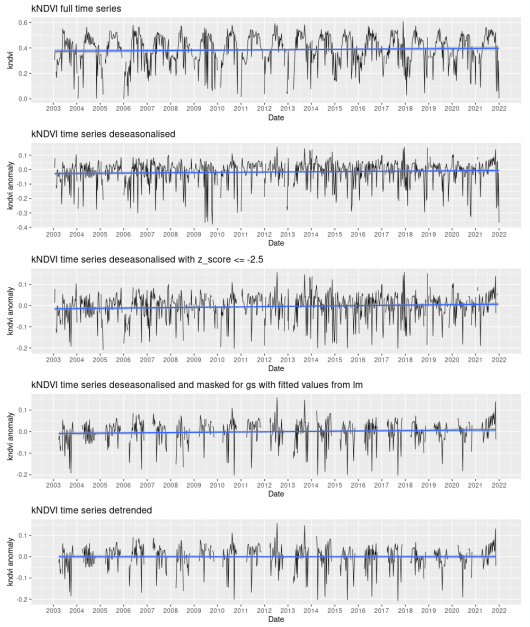
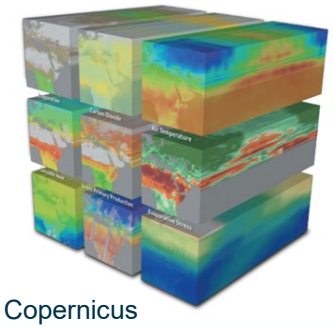




Copernicus

Extract the FSD - resilience relationship while controlling for confounding environmental factors

Time series

Vegetation
kNDVI

MODIS
8-day time series at 500m (2003-2021)

Climate
Temperature
Precipitation
VPD
Solar Radiation

ERA5
8-day time series at 10km (2003-2021)

Static

Structural Diversity
FSDH
FSDV
FSDH+V

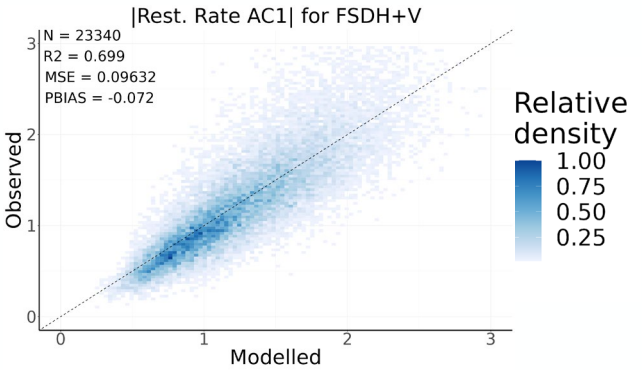
GEDI
Single snapshot at 30m (2019-2022)

Other
Topo. Diversity
Soil Carbon
Forest Cover

Single snapshot 25m
Single snapshot at 250m
Single snapshot at 30m (2000-2021)

Long-term/static stats at 5km from forests:
- Rest. Rates (vegetation)
- AC1 (anomalies)
- Climate variability (CV)
- Background climate (μ)

Static layers at 5km from forests



RANDOM FOREST
Rest. Rate = kNDVI (μ) + climate (AC1, CV, μ) + 1 Diversity metric + FC + SC + Topo. Div.

Outputs:
- Feature importance ranking
- Partial dependence
- Individual conditional expectations

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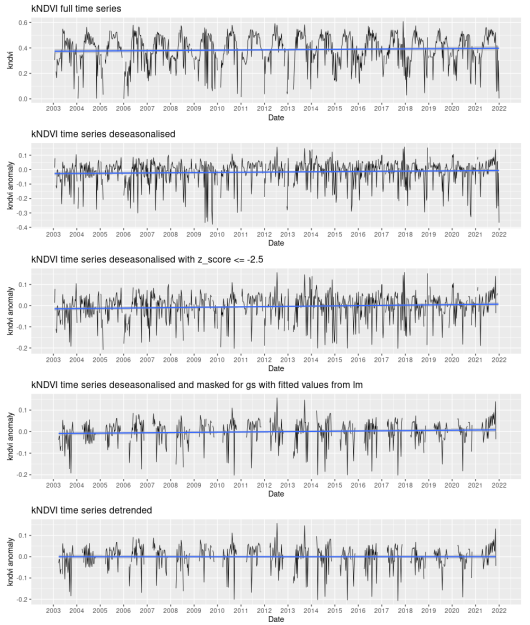

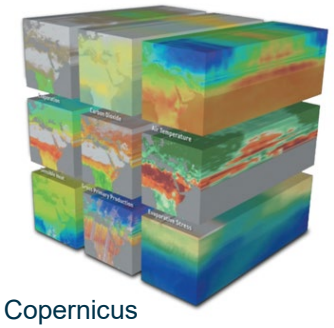

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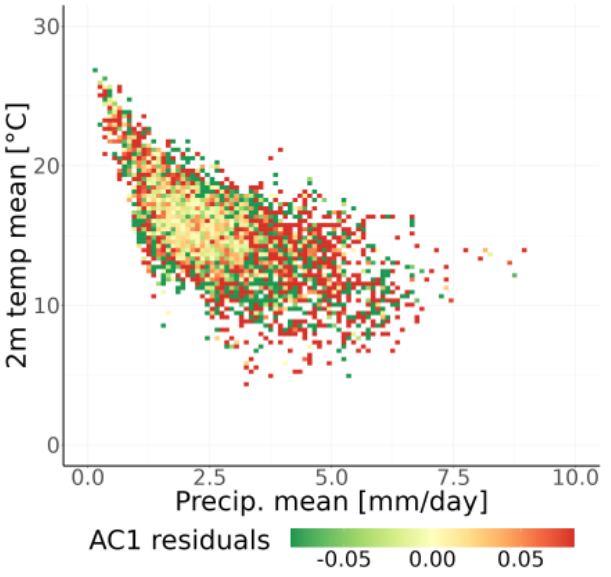

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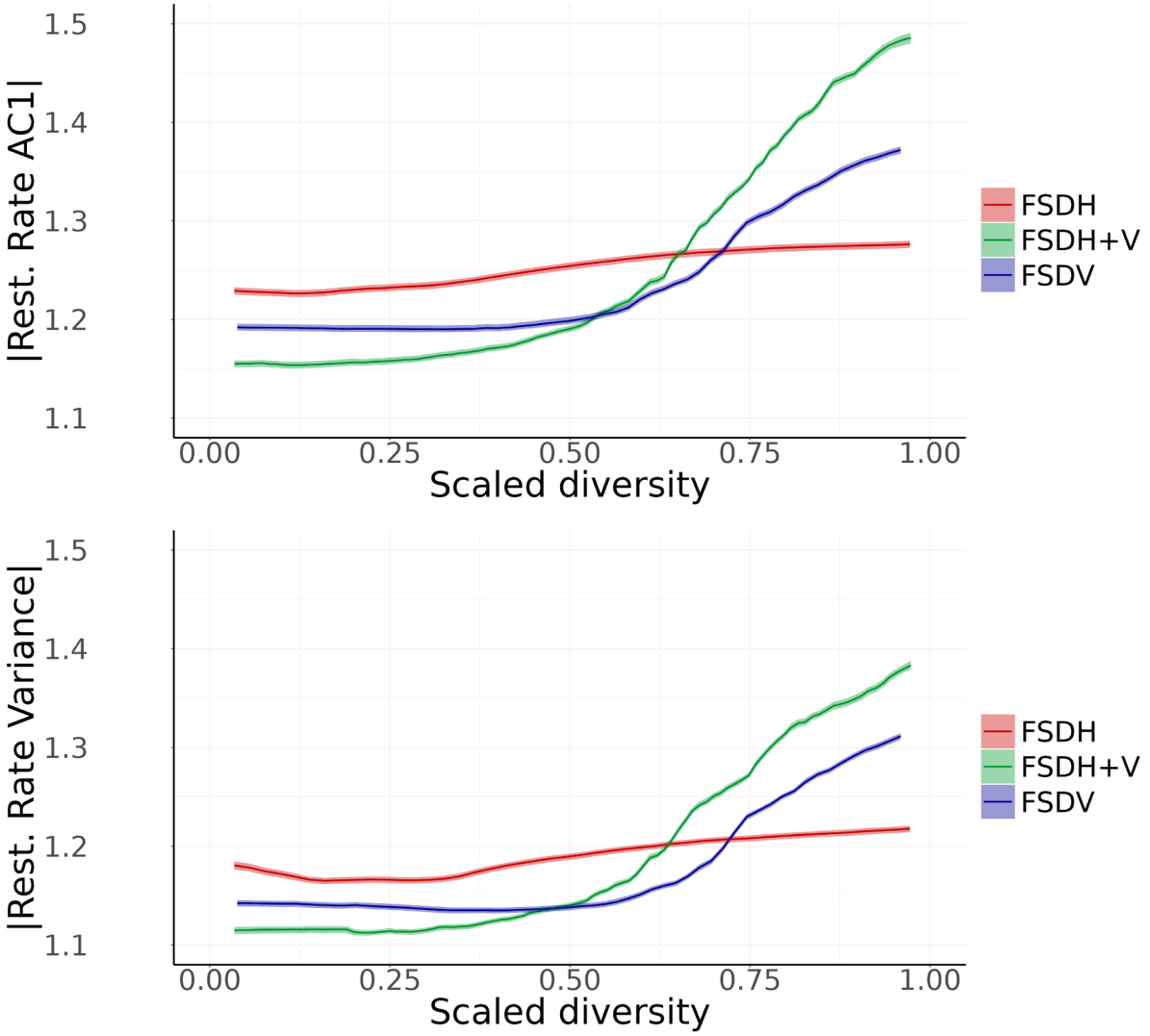
FSDH = Horizontal FSD
FSDV = Vertical FSD
FSDH+V = Combined FSD

Results: FSD – resilience 'global' relationship

- Partial dependence of resilience on FSD
- Controlling for all the model variables averaged globally and varying FSD – what is the effect on resilience?
- Significant ($p < 0.01$) positive relationship between resilience and diversity
- **<u>Combined diversity (complexity within the canopy substructure) is more important than variability in canopy height for resilience</u>**

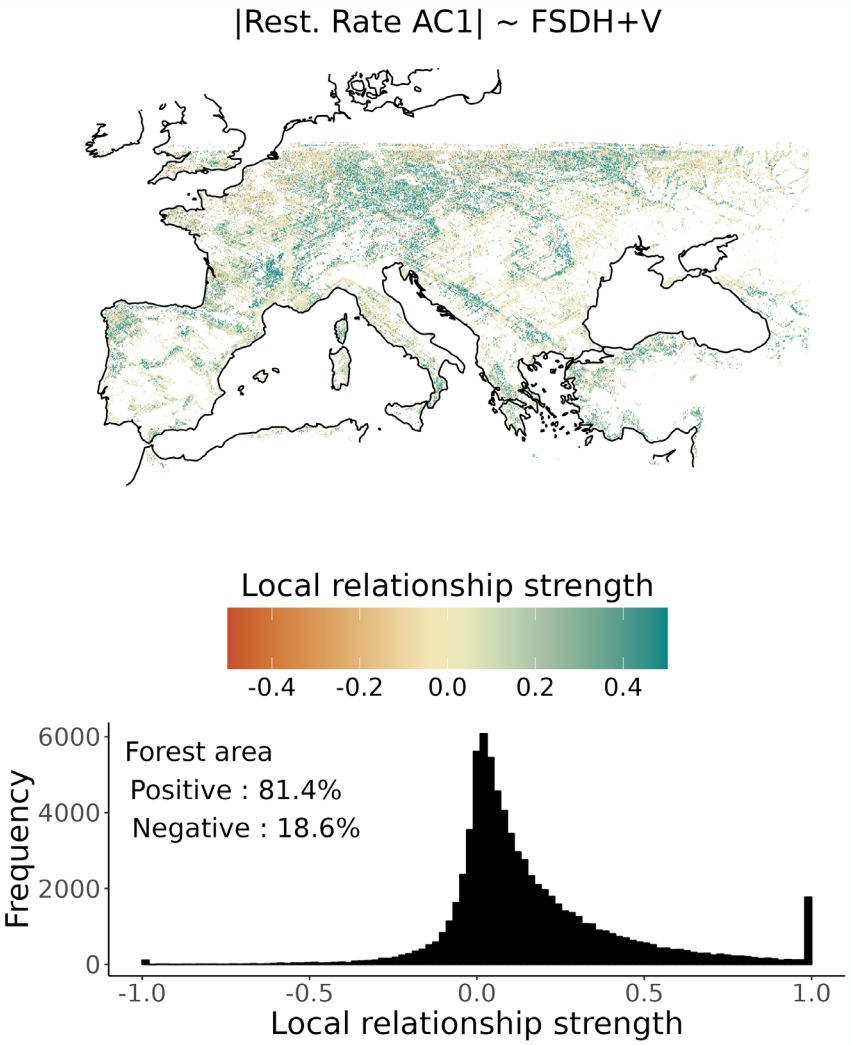


Quantifying the relationship between forest structural diversity and forest resilience

FSDH+V = Combined FSD

Results: FSD – resilience local relationship

- Local partial dependence of resilience on FSD
- Controlling for all the model variables at pixel level and varying FSD – what is the effect on resilience?
- The derivative gives the local level relationship direction and strength
- **<u>As we increase FSDH+V, Rest. Rate AC1 increases in 80% of South/Central European forests</u>**

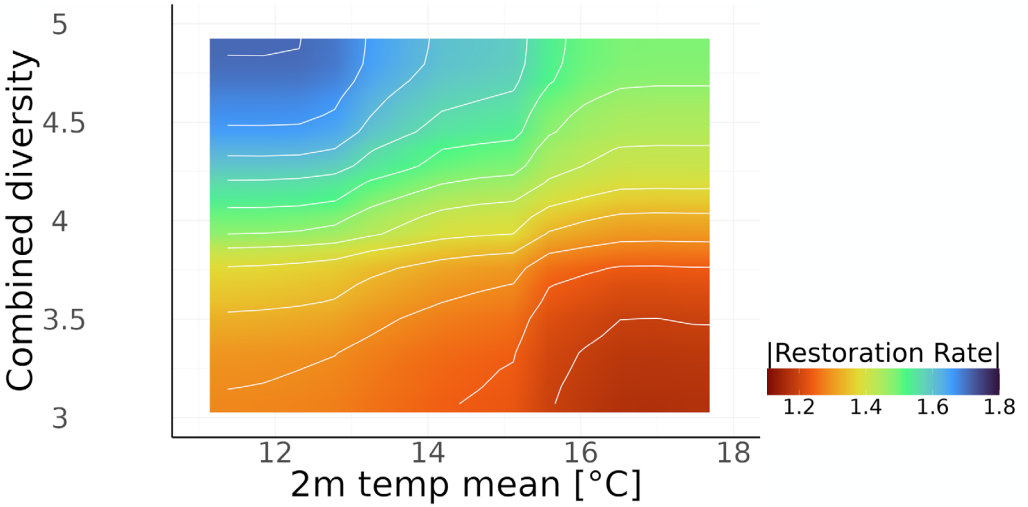


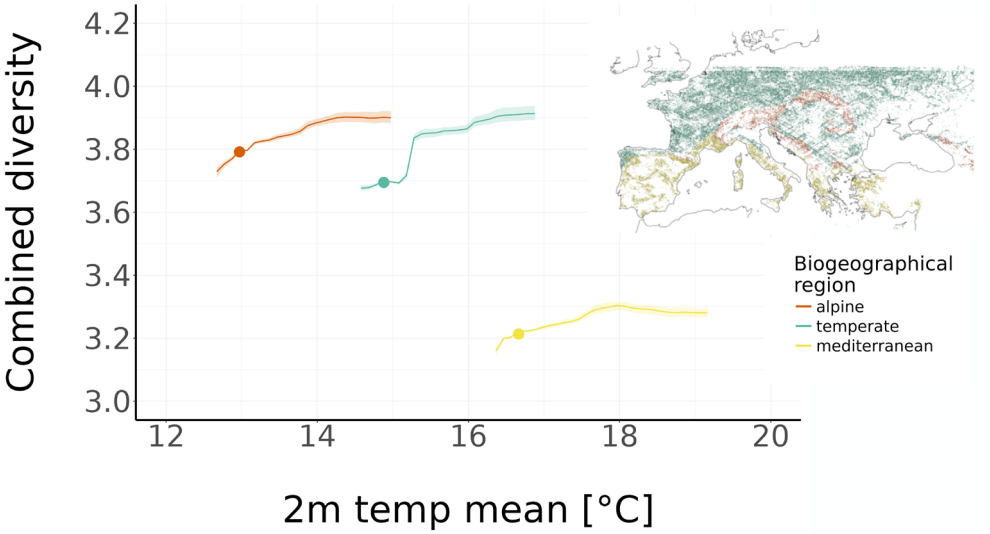
Quantifying the relationship between forest structural diversity and forest resilience

FSDH+V = Combined FSD

Results: FSD - diversity – temperature relationship

- Partial dependence of resilience on FSD as a function of temperature
- Isolines of constant resilience in a FSD – temperature space
- As temperatures rise, resilience declines – unless FSD also increases
- **Compensating 1◦C short-term increase in temperature requires 14% relative increase in the median FSDH+V for the temperate region**





Quantifying the relationship between forest structural diversity and forest resilience

Conclusions

- There is a relationship between FSD and forest resilience and more structurally diverse forests are more resilient
- Canopy substructure complexity is more important than diversity in forest height, and this is important for focusing management practice
- In the near-term, increases in FSD may compensate for the resilience loss associated with warming temperatures

Quantifying the relationship between forest structural diversity and forest resilience

Conclusions and future perspectives

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- Expand the analysis global
- Resilience to drought, heat and CHD extreme events

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Enhanced structural diversity increases forest resilience and may compensate climate-driven declines

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Paper submitted!

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THANK YOU!

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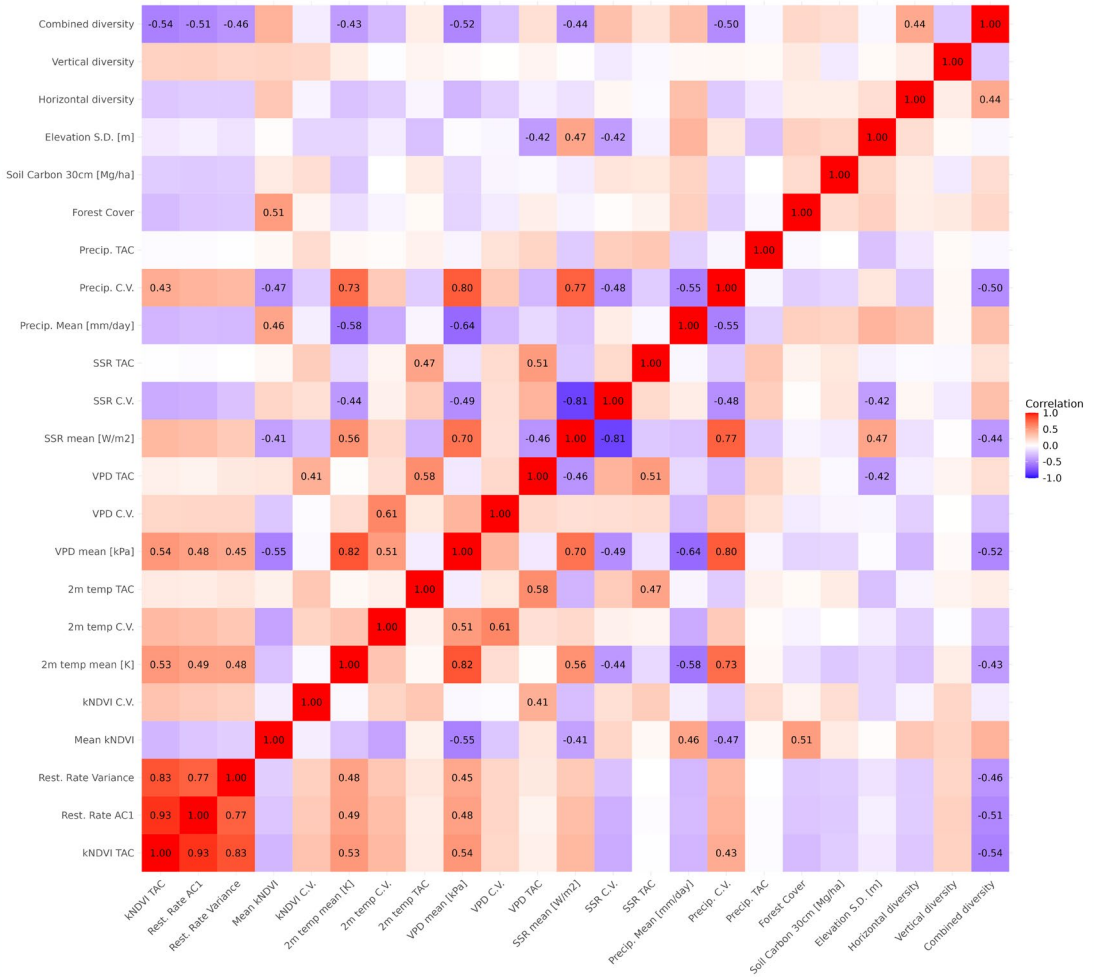

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