Assessing the relationship between European forest structural diversity and resilience in a warming climate

Mark Pickering, Agata Elia, Marco Girardello, Gonzalo Oton, Matteo Piccardo, Samuele Capobianco, Giovanni Forzieri, Mirco Migliavacca, Alessandro Cescatti

European Commission Joint Research Centre, Ispra, Italy
Why?

- We are observing declines in vegetation resilience under climate change
- What makes forests resilient? What can we do?
Why?

- We are observing declines in vegetation resilience under climate change
- What makes forests resilient? What can we do?
Resilience

• Engineering resilience: Restoration rate (\( \lambda \)) at which a system returns to equilibrium

\[
\frac{dx}{dt} = \lambda x + \sigma \frac{d\epsilon}{dt} ; \quad x(t) = x_0 e^{\lambda t} + \sigma \epsilon
\]

\[
x(t_{n+1}) = \alpha x(t_n) + \sigma \epsilon(t_n) + c ; \quad \alpha = e^\lambda = AC
\]

• With autocorrelation AC, variance \( V[x] \) and stochastic term \( \sigma \epsilon \)

• Defines Ornstein-Uhlenbeck process: mean-reverting random walk

Metrics relating to system memory

| Rest. Rate AC1 | \( |\ln(\alpha)| \) |

Metric relating to system stability

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

Rates often defined as negative (restoring equilibria) in literature
Here we consider the absolute value such that ↑ Rate = ↑ Resilience
As rates approach zero we see slowness in the system (CSD)
Vegetation data

- Resilience in proxy for forest productivity

\[ k\text{NDVI} = \tanh \left( \frac{NDVI^3}{\left|NDVI\right|} \right) \]

Camps-Valls et al., 2021

- Take forest masked pixels (500m) removing loss/change
- Remove the dominant seasonal cycle
- Filter (clouds) outlier points
- Correct the long term trend (CO2 fert, GW, etc)
- Aggregate to 5km

- Result: pixelwise time series of kNDVI perturbations from seasonal average
Vegetation data

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- More positive (blue) = lower autocorrelation/variance
- But, we can’t compare the ‘resilience’ of spatial pixels yet!
What determines TAC & Variance

- Aridity dominates
- Short and long term climate factors & variability
- Forest density, soil quality, etc

VOD + NDVI Rest. Rate with aridity

Smith, T and Boers, N 2023

Vegetation resistance against drought

Keersmaecker et al. 2015

TAC diver by latitude

Forzieri G. et al 2022
Vegetation Structure

- GEDI maps forest Lidar waveform from ISS
- Gives us relative canopy heights (RH) and forest canopy cover
Structural Diversity

- GEDI maps forest Lidar waveform from ISS
- Gives us relative canopy heights (RH) and forest canopy cover
- Several metrics of structural diversity computed across 5km pixel:

**Horizontal**

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

**Horizontal & Vertical**

Shannon Entropy = $$- \sum p_i \log(p_i)$$

$$\{RH50, RH75, RH98, CC\}$$

**Vertical**

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

Higher S.D. = More diversity in canopy height

Higher Entropy = More diversity in canopy structure

More negative = More diversity in vertical structure

See future dataset paper: "A dataset on the diversity of canopy structure of European Forests" Marco Girardello, Gonzalo Oton, Matteo Piccardo, Mirco Migliavacca, Alessandro Cescatti
Modelling Framework

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

- **Climate**
  - Temperature
  - Precipitation
  - VPD
  - Solar Radiation
  - ERAS 8-day time series at 10km (2003-2021)
  - Long-term/static stats:
    - TAC (anomalies)
    - Climate variability (CV)
    - Background climate (µ)

- **Structural Diversity**
  - S.D.(RH98)
  - Shannon Entropy
  - Excess Kurtosis
  - 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)

**RANDOM FOREST**

Restoration Rate =

\[ \text{kNVDI } (\mu) + \text{climate } (\text{TAC CV } \mu) + \]

1. Diversity metric
2. FC + SC + Topo div

**Outputs:**
- Feature importance ranking, partial dependence, etc

**Copernicus**

**OpenLandMap**
Modelling Framework

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**Restoration Rate**
\[
\text{Restoration Rate} = k\text{NDVI} + \text{climate (TAC CV)} + \text{1 Diversity metric} + F\text{C} + S\text{C} + \text{Topo div}
\]

**Outputs:**
- Feature importance ranking, partial dependence, etc

**Long-term/static stats:**
- TAC (anomalies)
- Climate variability (CV)
- Background climate (\(\mu\))

**Random Forest**

**OpenLandMap**

**Copernicus**
Diversity-Resilience relationship

- Controlling for all the model variables except diversity – what is the effect on resilience?
- Europe-wide relationship between the different diversity and resilience metrics

Resilience metric

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

Rest. Rate AC1 = |ln(\alpha)|
Diversity-Resilience relationship (local)

- Individual conditional expectation (ICE) figures
- Control each variable at the local pixel level value and allow the diversity metric to vary
- Gives the local level relationship direction and strength
- As we increase diversity, resilience metric increases
Diversity-Resilience-Temperature relationship

What is the relationship as a function of temperature?

As temperatures rise, resilience declines – unless diversity also increases.
Can diversity offset resilience decline?

Isolines of constant resilience (current mean for that BGR)

As temperatures rise, resilience declines – unless diversity also increases
Summary

- There is a relationship between forest structural diversity and forest resilience: more structurally diverse forests are more resilient.
- Canopy complexity is more important than diversity in forest height.
- In the near-term, increases in forest structural diversity may compensate for the resilience loss associated with warming temperatures.
- This is particularly true for Mediterranean species which may be more adapted to aridity.

Questions?
Structural Diversity

- GEDI maps forest Lidar waveform from ISS
- Gives us relative canopy heights (RH) and forest canopy cover
- Several metrics of structural diversity computed across 5km pixel:

**Horizontal**

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

Shannon Entropy = \( - \sum p_i \log(p_i) \)  
\( \{RH50, RH75, RH98, CC\} \)

**Vertical**

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

Higher S.D. = More diversity in canopy height

Higher Entropy = More diversity in canopy structure

More negative = More diversity in vertical structure
Feature Importance

- Build separate models for each diversity metric
- Build separate models for each resilience metric
- Resulting model has high $R^2$ and low bias
- Different diversity metrics – differences in importance
Vegetation resilience
Model Performance

Rest. Rate AC1 for S.D. in RH 98 [m]

- N = 23340
- $R^2 = 0.836$
- MSE = 0.09653
- PBIAS = 0.073

Test. Rate Variance for S.D. in RH 98 [m]

- N = 23340
- $R^2 = 0.755$
- MSE = 0.1148
- PBIAS = 0.087

Rest. Rate AC1 for Shannon Entropy

- N = 23340
- $R^2 = 0.835$
- MSE = 0.0971
- PBIAS = 0.073

Test. Rate Variance for Shannon Entropy

- N = 23340
- $R^2 = 0.753$
- MSE = 0.11547
- PBIAS = 0.087

Rest. Rate AC1 for Excess kurtosis

- N = 23340
- $R^2 = 0.837$
- MSE = 0.09608
- PBIAS = 0.073

Test. Rate Variance for Excess kurtosis

- N = 23340
- $R^2 = 0.758$
- MSE = 0.11351
- PBIAS = 0.086
Diversity-Resilience Relationship
Diversity-Resilience Relationship With Temperature