Resilience dynamics of European forests under consecutive drought events

Agata Elia[1] (Agata.Elia@esa.int), Mark Pickering[2], Giovanni Forzieri[3], Alessandro Cescatti[4], Diego Fernandez Prieto[1]

[1]European Space Agency, ESA ESRIN, Frascati, Italy; [2]Joint Research Centre Consultant, Ispra, Italy; [3]Department of Civil and Environmental Engineering, University of Florence, Florence, Italy; [4]Joint Research Centre, European Commission, Ispra, Italy

Outlook

Using the temporal autocorrelation of the normalized difference vegetation index, we aimed at investigating:

- **Do trends in AC1 reveal the occurrences of drought events in European forests?**
- **Is there a consistent effect of consecutive drought events on the resilience of European forests as measured by AC1?**

1. Background and introduction

The increasing frequency and persistence of drought and compound hot and dry extreme events have raised growing concerns about the future of forest ecosystems, given the strong link between climatic stress, tree mortality, and declining biomass carbon stocks (Senf et al., 2020; Li et al., 2025). European forests are particularly vulnerable, as the continent is among the regions most affected by compound hot and dry extremes in terms of both spatial extent and duration (Weynants et al., 2025). Assessing how forests respond to repeated drought events is therefore important in understanding ecosystem vulnerability under ongoing climate change and to pinpoint adaptation strategies.

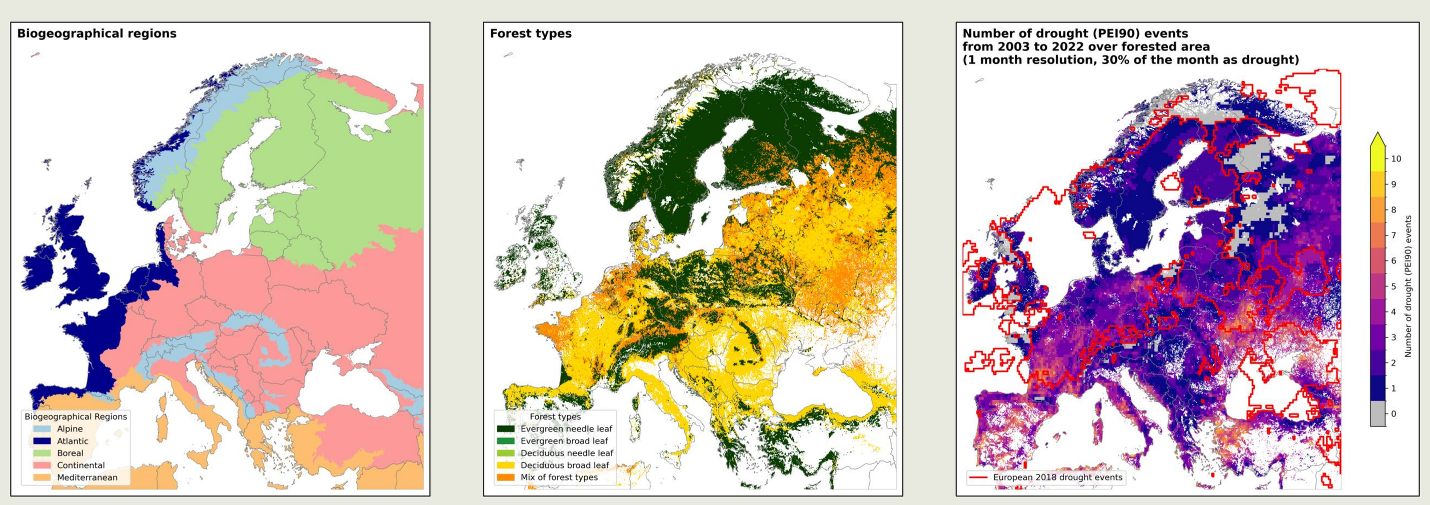
In this study we aim at investigating the dynamics of the resilience of stable European forests where repeated drought events occur. Using a 2003-2022 time series of Normalized Difference Vegetation Index (NDVI) anomalies at an 8-day temporal resolution from MODIS satellites, we quantify ecosystem resilience via the lag-1 temporal autocorrelation (AC1) computed over a yearly moving window. Drought events are retrieved from the Dheed global database of dry and hot extreme events based on ERA5 (Weynants et al., 2025).

Trends in AC1 in between the events are then assessed to identify dynamics in forest resilience across Europe and to explore the potential influence of drought occurrences, highlighting existing cumulative impact of repeated extreme events on forest resilience.

2. Datasets and study area

- Daily time series of surface reflectance at 500m spatial resolution from MODIS Terra (MOD09GA) and Aqua (MYD09GA) datasets, from 2003 to 2021 (Vermote et al., 2021)
- Hansen Global Forest Change v1.11 (2000-2024) (Hansen et al., 2013).
- Dheed global database of dry and hot extreme events based on ERA5 (Weynants et al., 2025). Droughts identified when daily differences between total precipitation and evapotranspiration averaged over the preceding 30, 90 and 180 days (PEI_30, PEI_90, PEI_180) are less than the 1st percentile of their respective distributions over time for the pixel (Weynants et al., 2025).

Our study focuses on the region represented in the following maps, using the presented adapted biogeographical regions (EEA, 2016) and forest types (Buchhorn et al., 2020) to aggregate obtained results. Furthermore, we identified the boundaries of the European 2018 drought events from the Dheed dataset, to be used as reference extreme since this drought was one of the most intense in terms of length and temperatures in Europe (Buras et al., 2020).



3. Methodology

DHEED v4 daily droughts and heatwaves at 0.25° 2003-2022 → Drought (PEI_90) daily events → Resampled at 8-day (last day) and monthly (30%) time scale → Resampled at 0.05° → Mask where NDVI

MODIS Terra/Aqua daily time series 0.005° 2003-2022 → 8-day time series of NDVI (mean) → Mask for stable forests based on Hansen → Resampled at 0.05° →

1 – Anomalies

$$NDVI_{anomaly_i} = NDVI_i - \overline{NDVI}_i^{clim}$$

2 – Outliers

$$\frac{NDVI_i - \overline{NDVI}_i^{clim}}{\sigma NDVI_i^{clim}} \geq -2.5$$

3 - Linear detrending

$$NDVI_{anomaly\ detrended_i} = NDVI_{anomaly_i} - \widehat{NDVI}_{anomaly_i}$$

4 – Growing season masked

→ AC1 computed over a rolling moving window of 1 year

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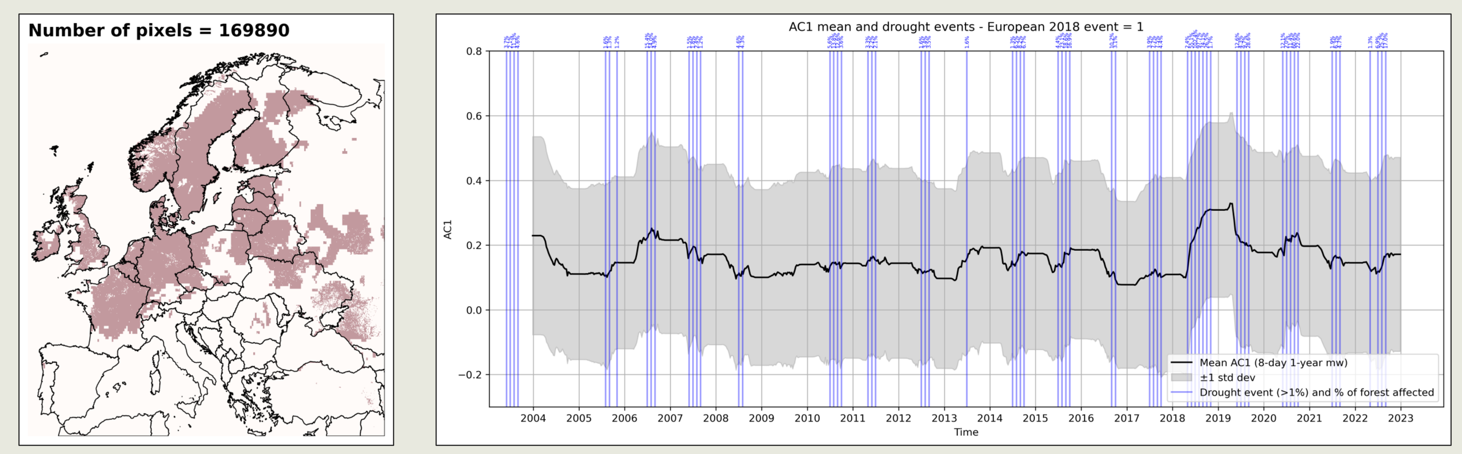
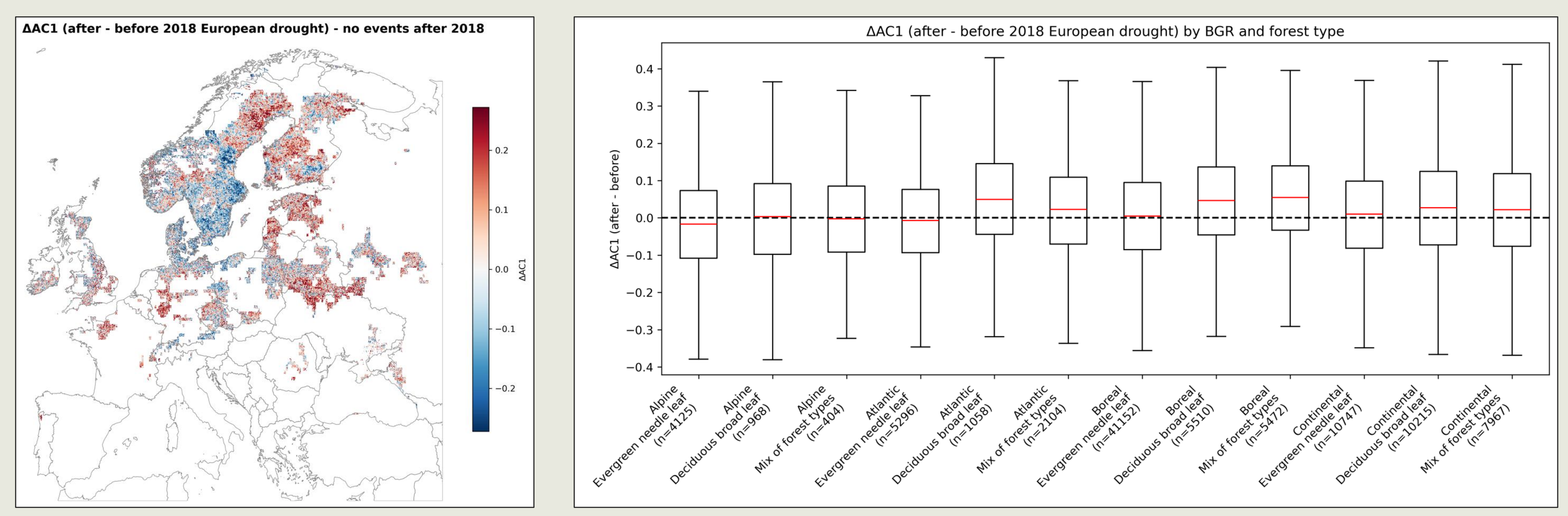
4. Results

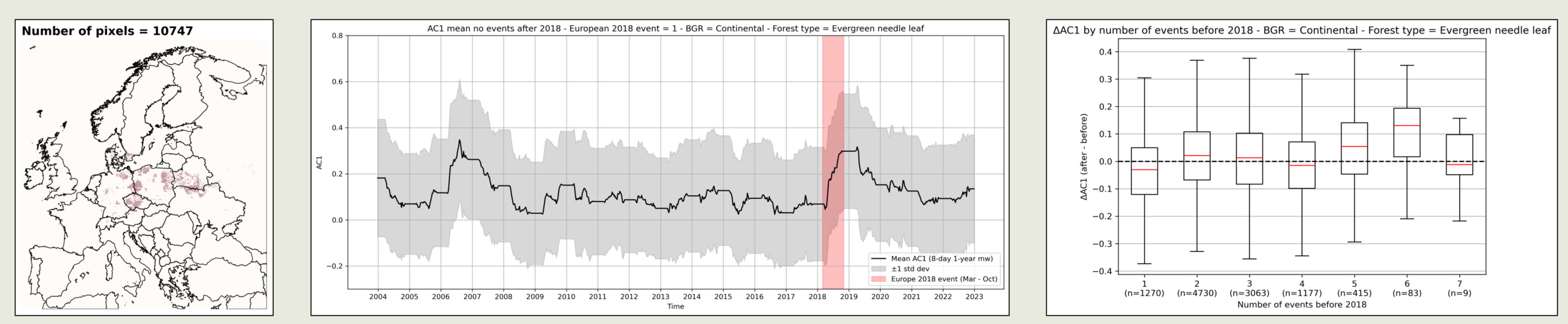
The time series of AC1 averaged across all pixels affected by the drought events in 2018 in Europe highlights a jump in AC1 corresponding to the 2018 drought. Blue lines corresponding to other drought events happening within the area across the time series (aerial percentage shown on top of the line) are also represented. We want to explore the impact of these drought events on forest' resilience.

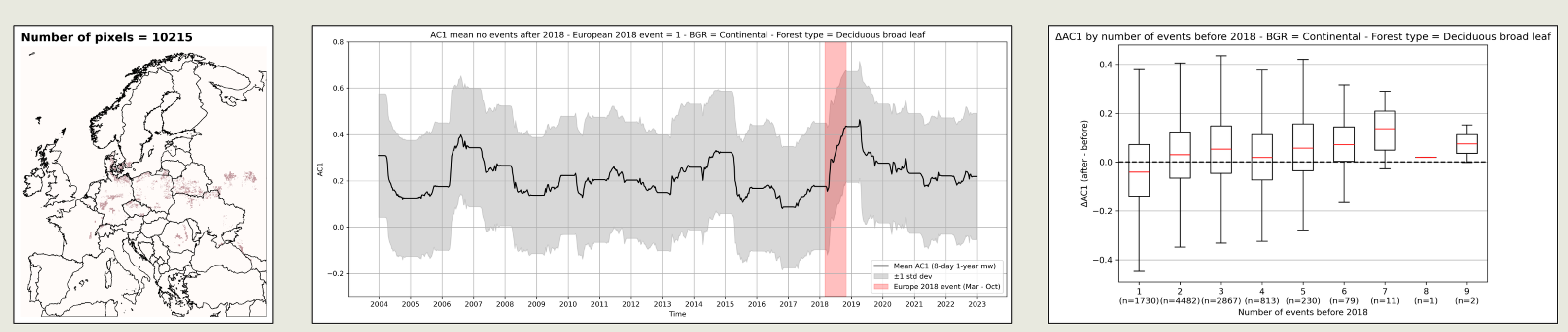


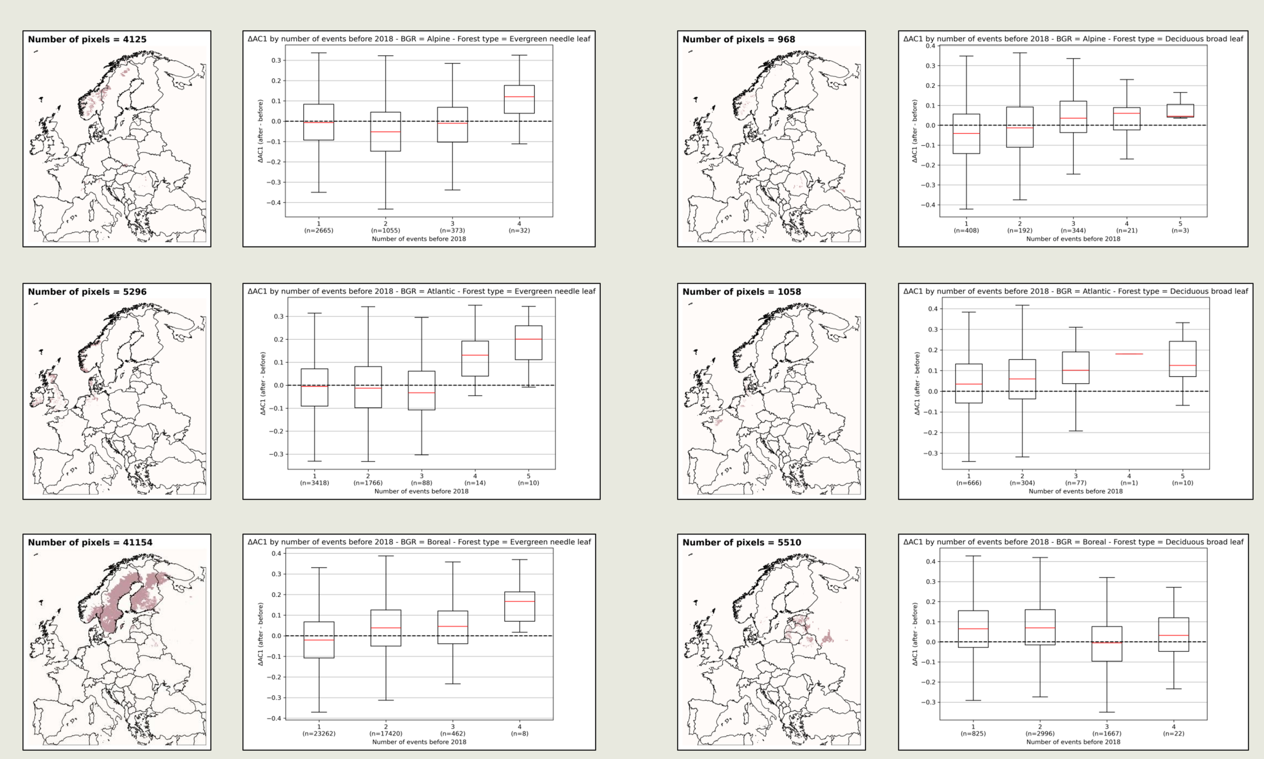
We therefore measured the ΔAC1 between after and before the 2018 drought for each forested pixel and then aggregated it by biogeographical region (BGR) and forest type. At first, we computed this ΔAC1 only for those forested pixels not experiencing any other drought event after 2018. ΔAC1 is computed as the difference between the average AC1 of the whole time series prior 2018 and the average AC1 in the three years following the second year after 2018.



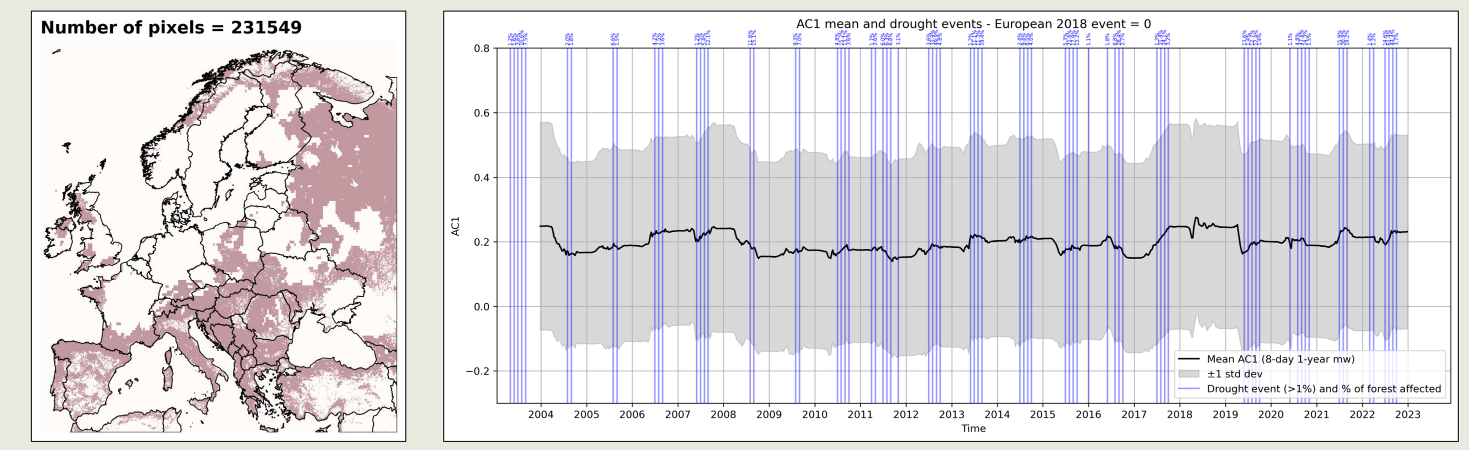
We then looked at the potential relationship between the ΔAC1 of forested pixels not experiencing any other drought after 2018, and the number of drought events preceding 2018. We explored this by BGR and forest type.

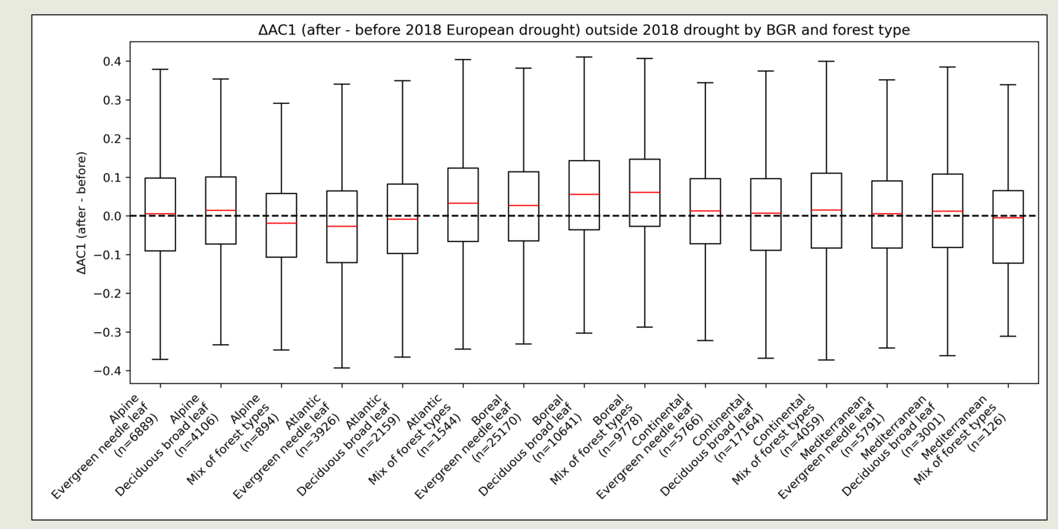




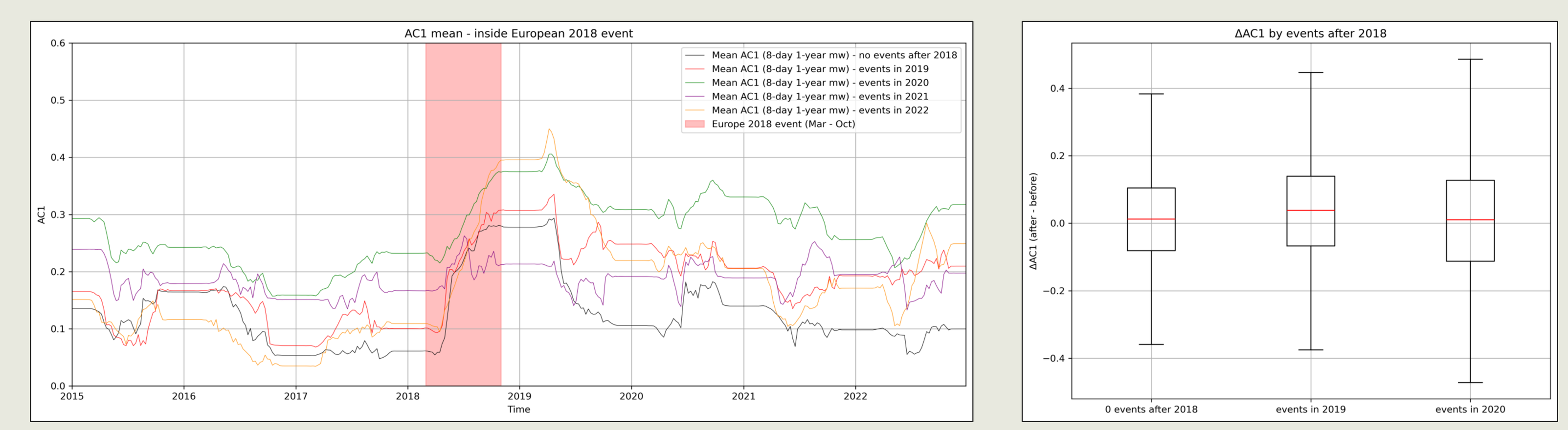


We then compared the previous results with the ΔAC1 in pixels not experiencing the 2018 drought events.





Finally, we started investigating the dynamics in AC1 according to the number of events following the 2018 European drought event. The time series of AC1 was averaged across all pixels affected by the drought events in 2018 but split in order to show separately the AC1 of forested pixels affected by none or subsequent droughts exclusively in one of the following years. The ΔAC1 was computed for forested pixels having events only in 2018, in 2018 and in 2019 only, in 2018 and 2020 only, as the difference between the average AC1 of the whole time series prior 2018 and the average AC1 in the remaining years following the first year after the last events affected year.



5. Discussion

The time series of AC1 appears to be sensitive to the drought events. The European 2018 drought have the strongest correspondence in terms of visible AC1 trends. Other events impacting smaller portions of the studied area also seem to correspond to peaks in the AC1 time series, even though the relationship between the amount of forest affected and the strength in the AC1 signal is not clear. In addition, some events seem not to impact the AC1 trend.

When looking at the ΔAC1 between after and before the 2018 event, results are quite variable in the region and between BGR and forest types. The highest impact in terms of resilience loss considered as an increased AC1 is shown by Atlantic deciduous broad leaf, Boreal deciduous broad leaf and Boreal mixed forest types.

The number of preceding drought events seems to exacerbate resilience loss following the 2018 European event for almost all BGR and forest types except for Boreal deciduous broad leaf.

A preliminary look at the consequences of post-drought events does not reveal strikingly separate behaviours.

Compared to another recent study (Wu et al., 2026) focused on multi-year droughts, the shorter length of the European 2018 drought may be one of the causes of the presented low sensitivity of AC1. Questions as the size of the moving window, sensitivity of NDVI to droughts, temporal resolution of NDVI data and how to best compute the ΔAC1 are also investigated to improve the sensitivity of the analysis.

6. References

Senf et al. (2020), *Nature Communications*
Li et al. (2025), *Nature Communications*
Weynants et al. (2025), *Earth System Science Data*
Vermote and Wolfe (2021a), NASA EARTHDATA
Vermote and Wolfe (2021b), NASA EARTHDATA
Hansen et al. (2013), *Science*
European Environment Agency (2016), Biogeographical regions in Europe
Buchhorn et al. (2020), Zenodo
Buras et al. (2020), *Biogeosciences*
Wu et al. (2026), *Nature Ecology & Evolution*