Supporting EU Climate Goals through Improved Satellite based Forest Monitoring and Modelling:

A suggested research roadmap

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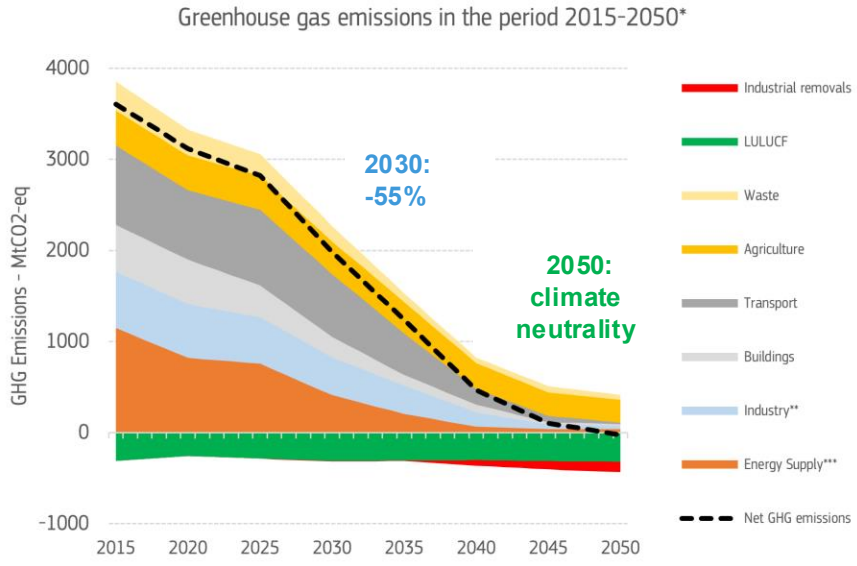
European Commission

Motivation

The EU Climate law requires a *balance* between anthropogenic GHG emissions and **CO_2 removals** by 2050



*Source: PRIMES, GAINS, GLOBIOM
**Excluding non-BECCS industrial removals
***Including Bioenergy with carbon capture and storage (BECCS)

The importance of the forest CO_2 sink will increase over time

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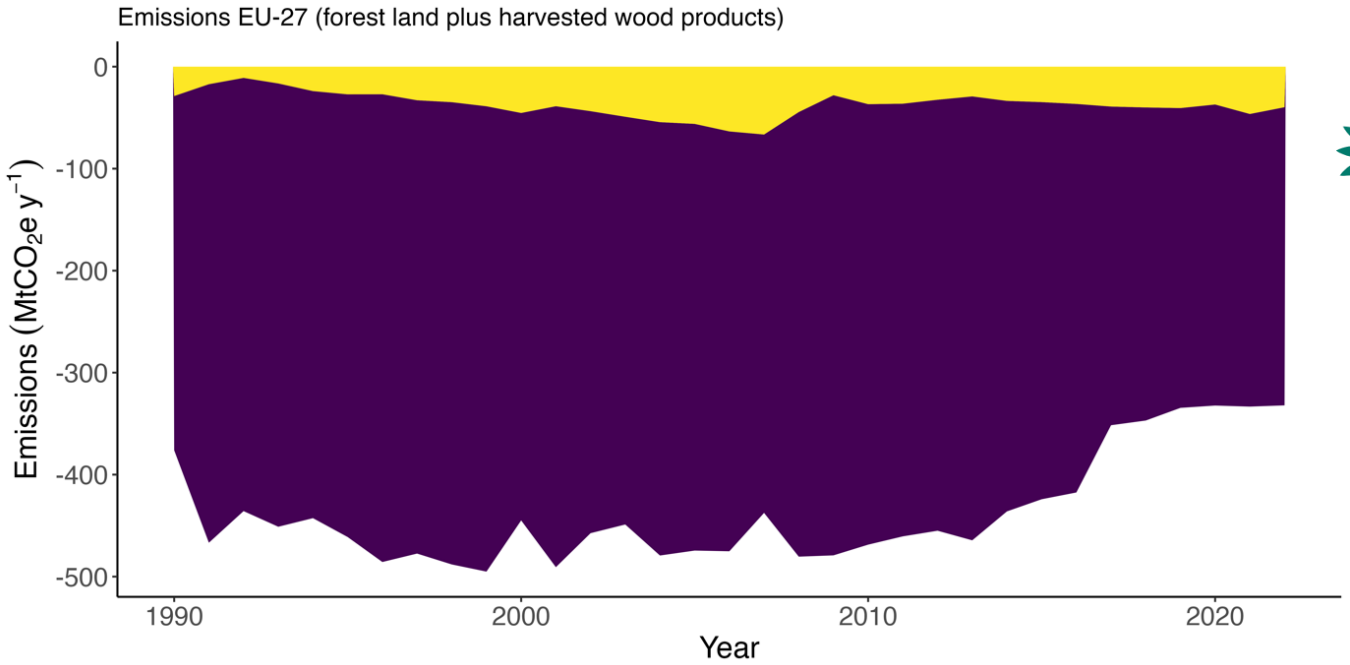
Motivation

Widespread decline of forest carbon sink in Europe



European Environment Agency

Figure based on 2024 EEA reporting

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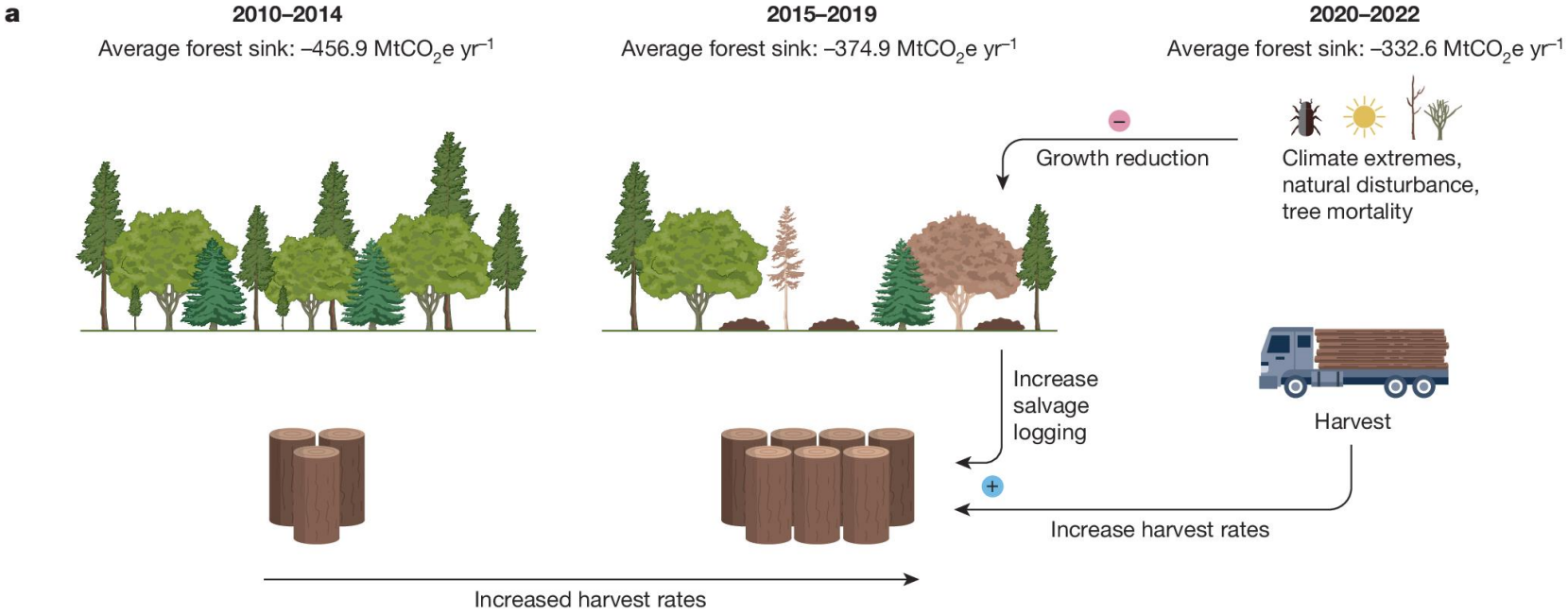
How can research support climate policies?

What are the causes?



Migliavacca et al., 2025, Nature, 643, 1203–1213

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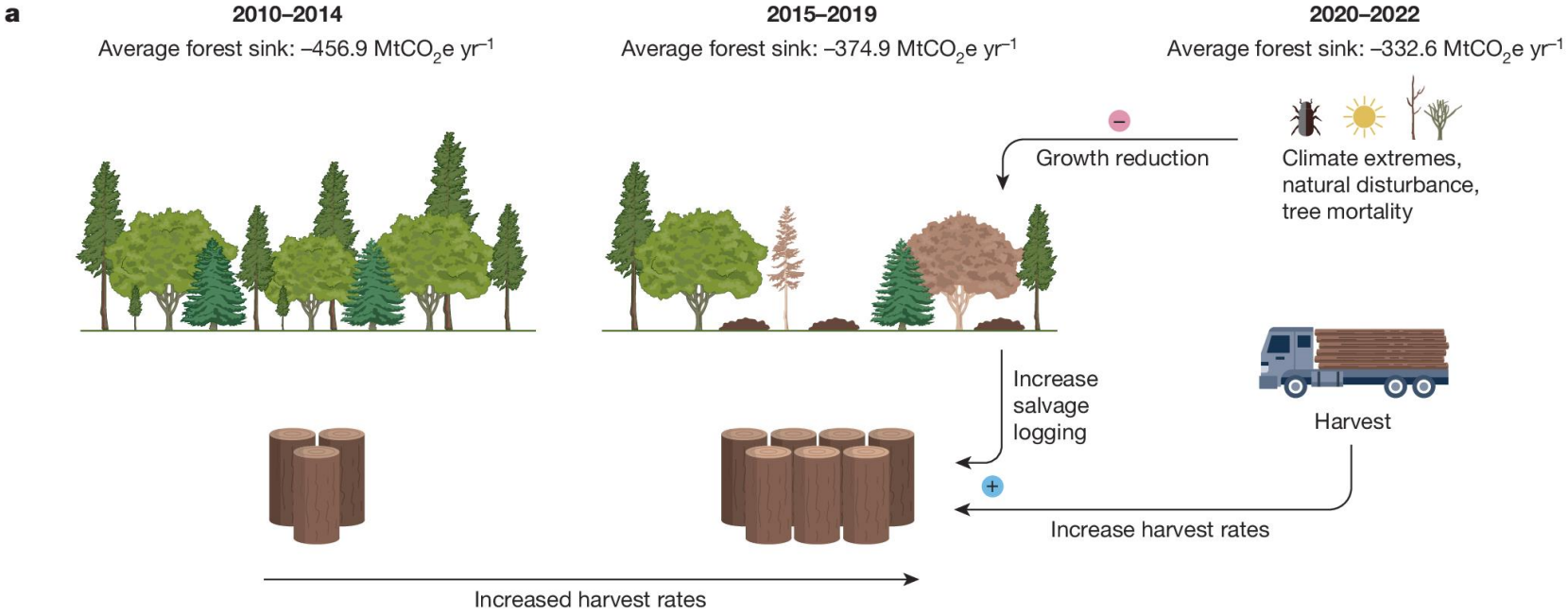
What are the causes?

How much is the importance of long-lasting vs controllable (mgmt) drivers?



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Solutions

- Biodiversity-oriented afforestation
- Harvest reduction
- Increase rotation length
- Increase stand-age diversity
- Improve deadwood management
- Increase storage in harvested wood products

- Understanding the impact of climate extremes on forests
- Understanding the role of biodiversity as a climate-extreme buffer
- Quantification of climate extremes–harvest feedbacks
- Increasing forest resilience (age diversity and climate-resilient species)
- Assisted tree migration

Aspects to consider

- Socioeconomic impacts of harvest reduction
- Long-term versus short-term effects of forest management decisions
- Progressive forest ageing and sink saturation
- Effects on soil carbon
- Impacts on water cycle and albedo

- Afforestation impact on water, albedo and biogeochemical cycles
- Long-term success of afforestation
- Assessment of climate-induced species bottleneck

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Research priorities to support policies

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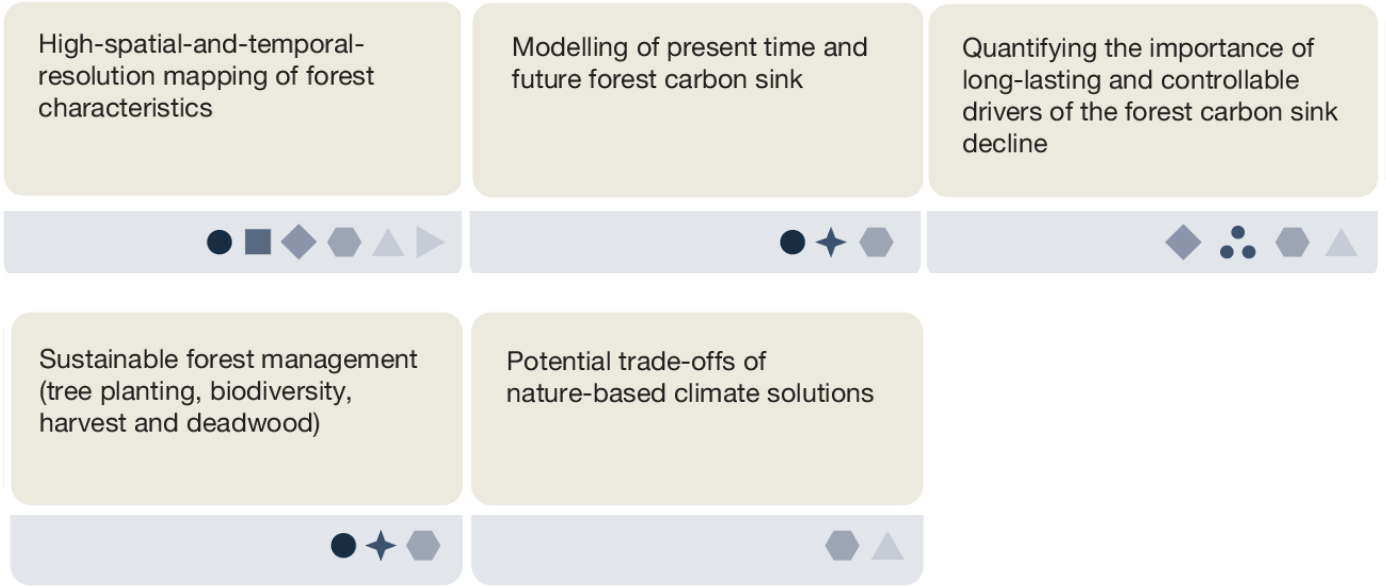

Modified from Migliavacca et al., 2025, Nature, 643, 1203–1213

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Research priorities to support policies

Research priorities

High-spatial-and-temporal-resolution mapping of forest characteristics

Modified from Migliavacca et al., 2025, Nature, 643, 1203–1213

Research priorities to support policies

Research priorities	Current solution
High-spatial-and-temporal-resolution mapping of forest characteristics	• New generation of products under development (for example, disturbance atlas, tree height, biomass)

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Research priorities to support policies

Research priorities	Current solution	Ways forward
High-spatial-and-temporal-resolution mapping of forest characteristics	• New generation of products under development (for example, disturbance atlas, tree height, biomass)	• Map key variables for policy support: forest management disturbance type, mortality (**S**) • Scalable and consistent biodiversity monitoring (**S**) • Building open datasets of tree mortality and biomass (**S**) • Adoption of privacy-preserving technologies to train machine-learning models (**S**) • Adapt the ground data to the needs of Earth observation (**M**)

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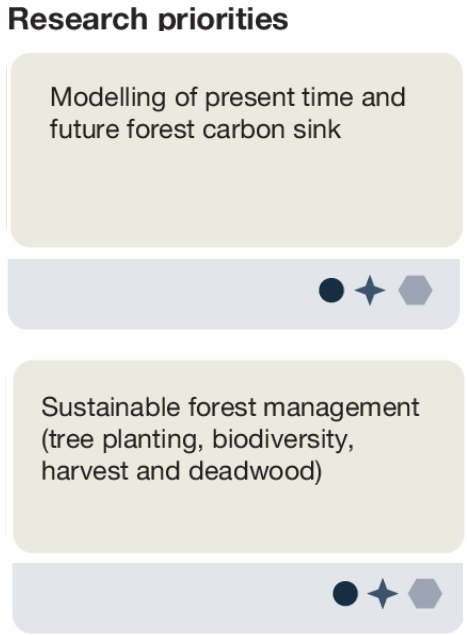
Example mapping forest Net Annual Increment

Modified from Migliavacca et al., 2025, Nature, 643, 1203–1213

Research priorities to support policies



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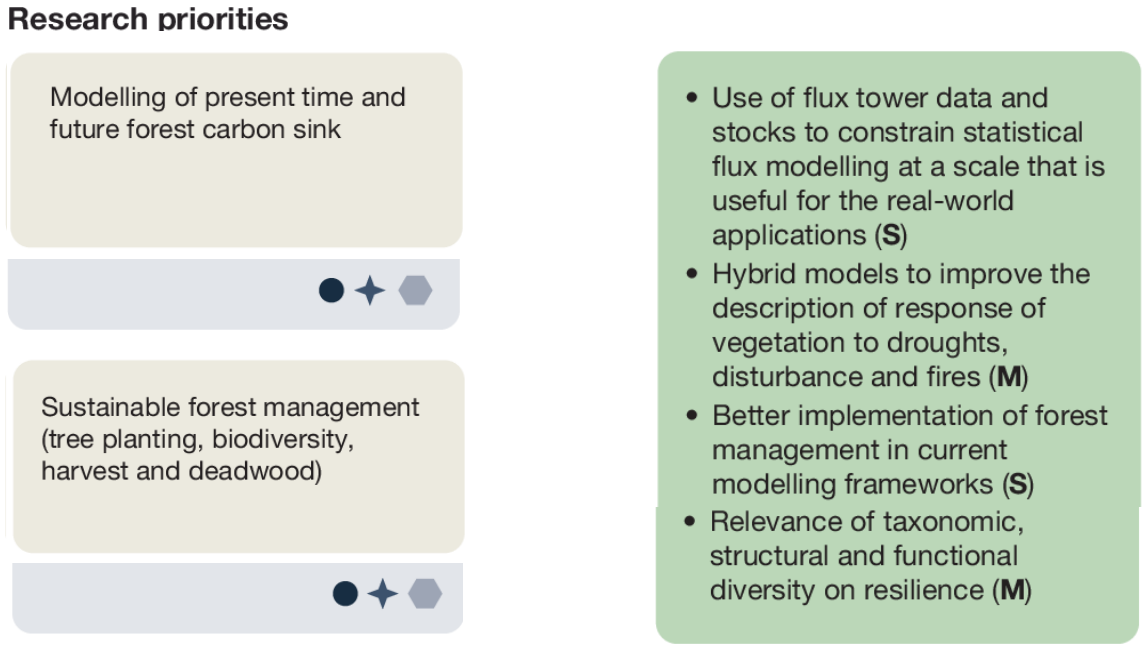
LULUCF | European Climate Law | Soil Monitoring Directive Proposal | Nature Restoration Law | Biodiversity strategy | Carbon Removals Certification | Forest Monitoring Law | Forest strategy

Research priorities to support policies



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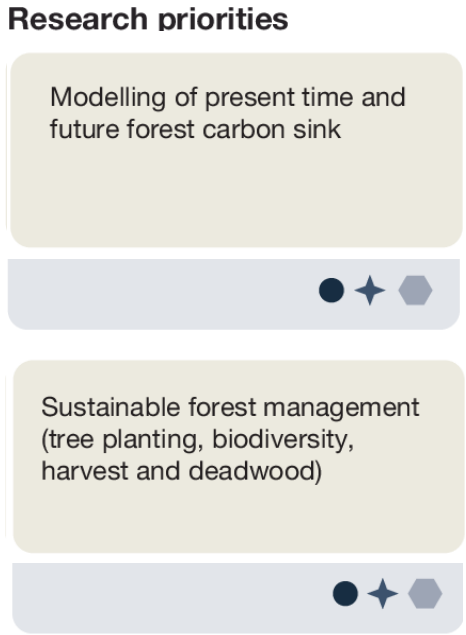

- Use of flux tower data and stocks to constrain statistical flux modelling at a scale that is useful for the real-world applications (**S**)
- Hybrid models to improve the description of response of vegetation to droughts, disturbance and fires (**M**)
- Better implementation of forest management in current modelling frameworks (**S**)
- Relevance of taxonomic, structural and functional diversity on resilience (**M**)

Importance of structural diversity as adaptation measure

Modified from Migliavacca et al., 2025, Nature, 643, 1203–1213

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Modelling carbon removals

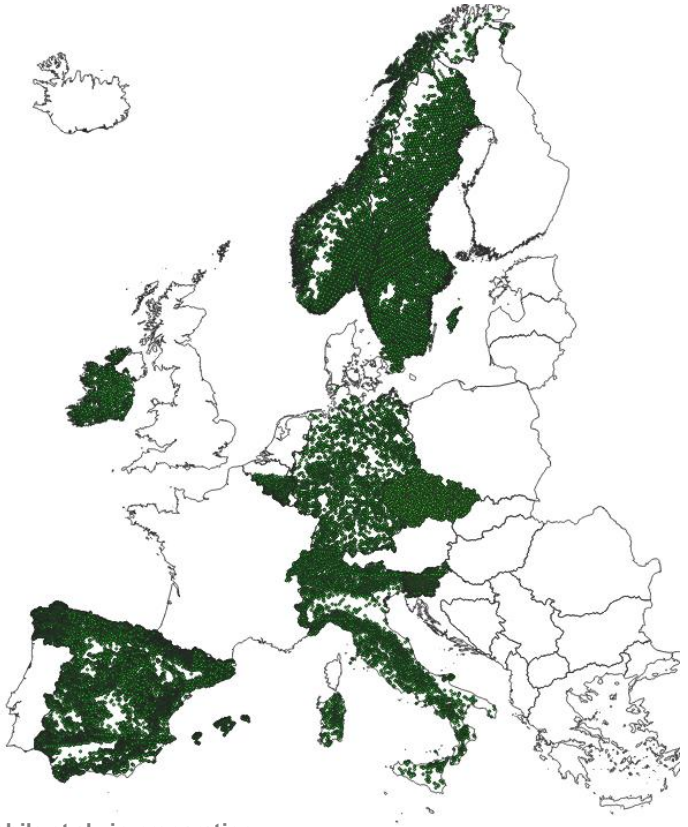
Modelling forest net annual increments (NAI) in support to the Carbon Removals and Carbon Farming (CRCF) combining EO and National Forest Inventory data

Monitoring forest net annual increment

Collection of co-located NFI and Sentinel 2/Copernicus data

Prediction Net Annual Increments (Machine/Deep learning)

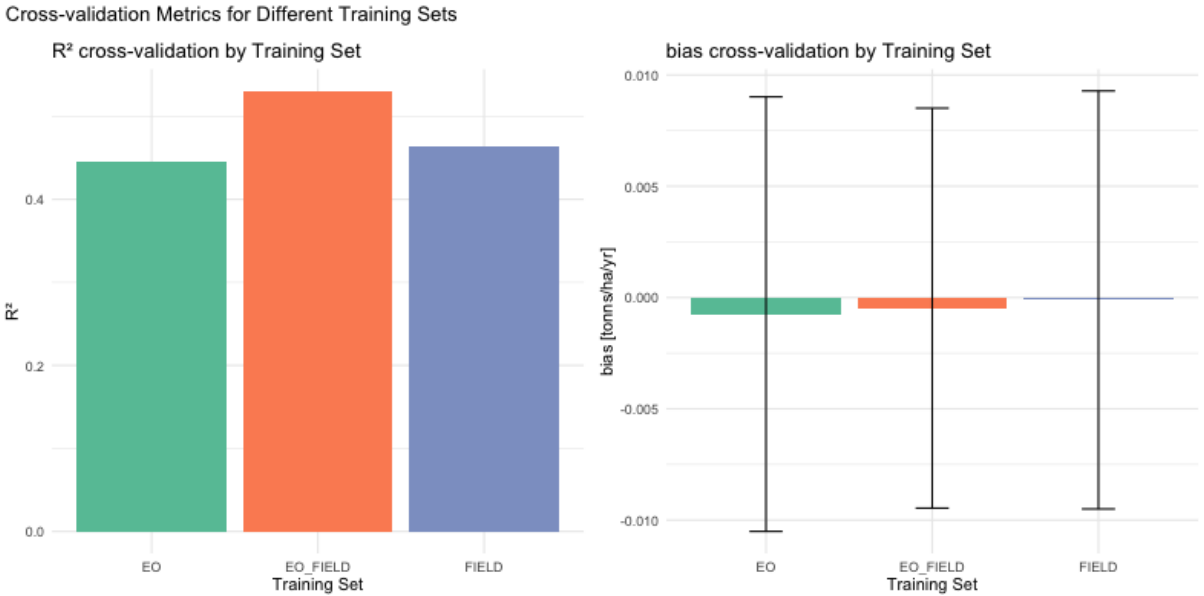
Prediction based on FIELD data and EO only



Avitabile et al., in preparation

PathFinder

Monitoring forest net annual increment



- Accuracy of EO ≈ FIELD for the application at EU-level
- Accuracy of FIELD + EO is the best
- Main predictors: AGB, Tree Cover, Species, Sentinel bands;
- Quantification tool for supporting the CRCF

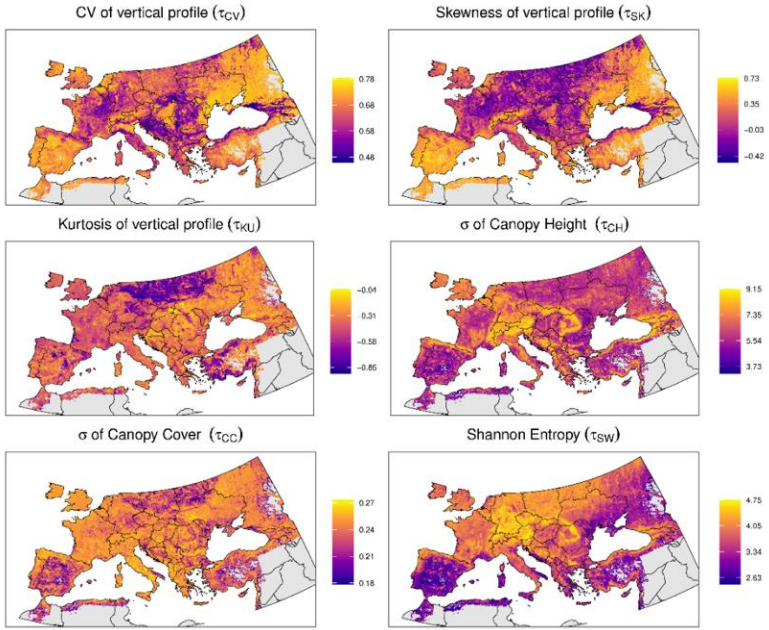
Avitabile et al., in preparation

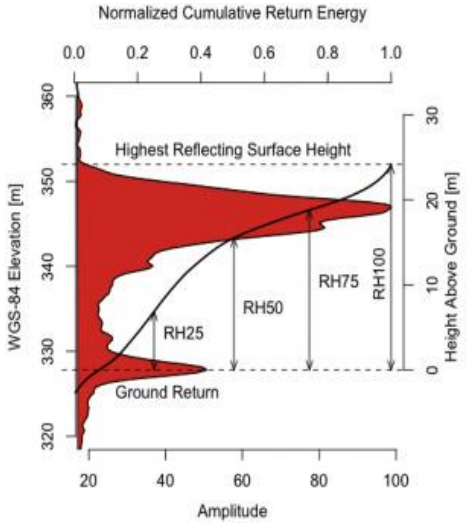
Resilience and diversity

Understanding the relationship between forest resilience and diversity (**structural**, **taxonomic** and functional) under climate change

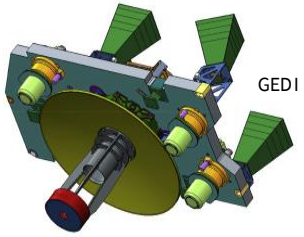
Forest Structural Diversity (FSD)

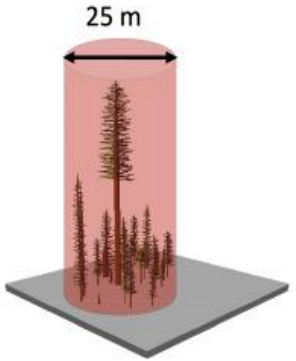
- GEDI on ISS (full-waveform LiDAR)
- Relative vertical profiles of canopy elements
- Structural diversity at 5km resolution





Dubayah, R., (2020)



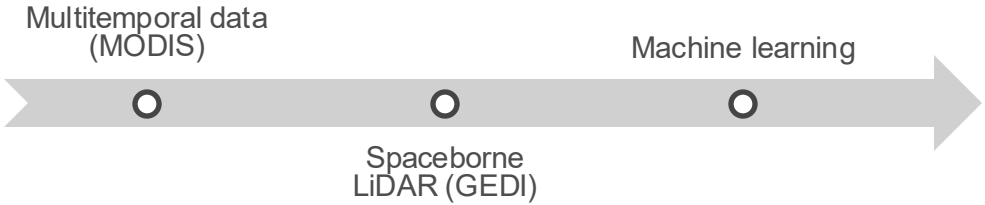


A dataset on the structural diversity of European forests

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

https://essd.copernicus.org/preprints/essd-2024-471/

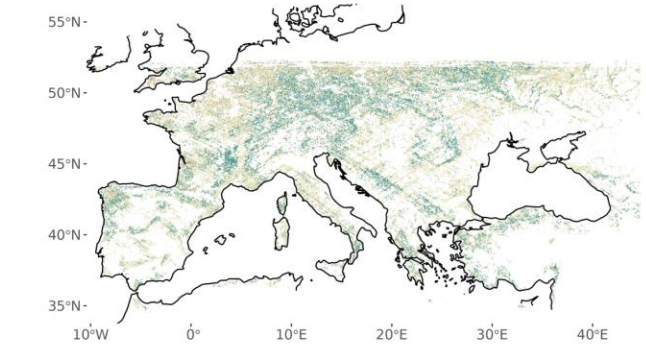
European forest resilience and diversity



How forest structural diversity shape forest resilience and recovery rates?

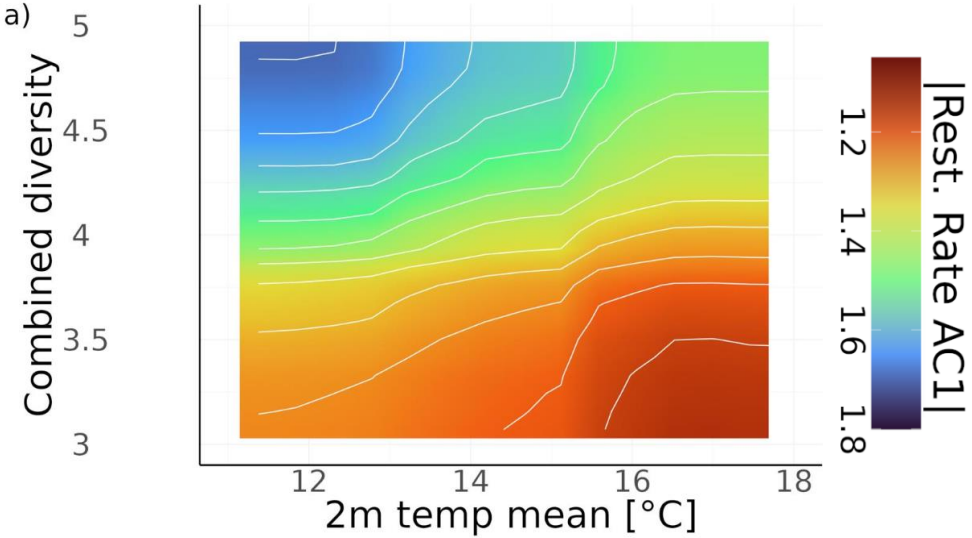
- 80% of EU forests show a **positive relationship** between resilience and structural diversity
- Increase forest resilience via policies that promote **canopy complexity** vs spatial diversity in canopy height.

Pickering et al., Comms Earth and Environment in press



Structural diversity as adaptation measure

- Isolines of constant resilience in the forest structural diversity – climate space
- As temperature rise, resilience declines, unless FSD also increases
- Compensating 1 ^{o}C increase requires 8-14% relative increase in the horizontal and vertical structural diversity



Pickering et al., Comms Earth and Environment (In press)

How can research support climate policies?

Timeliness and **EU-wide consistent** spatially resolved information on state of forests, stock changes and carbon removals dynamics

Assessing the relative contribution of the **long-lasting** vs **controllable drivers**

Develop tools to assess **co-benefit and trade offs (**beyond carbon sequestration) of Nature based climate solution and forest management decisions