Earth observations for aboveground carbon estimation

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with contributions by many

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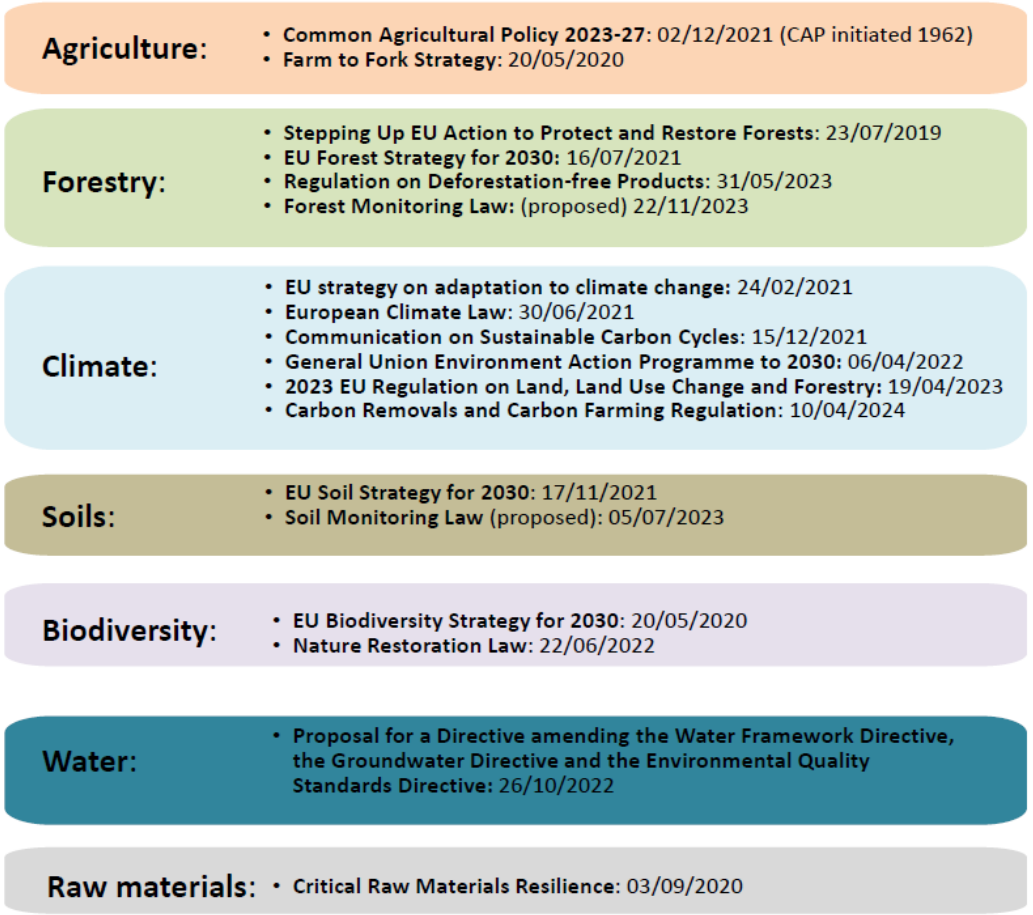
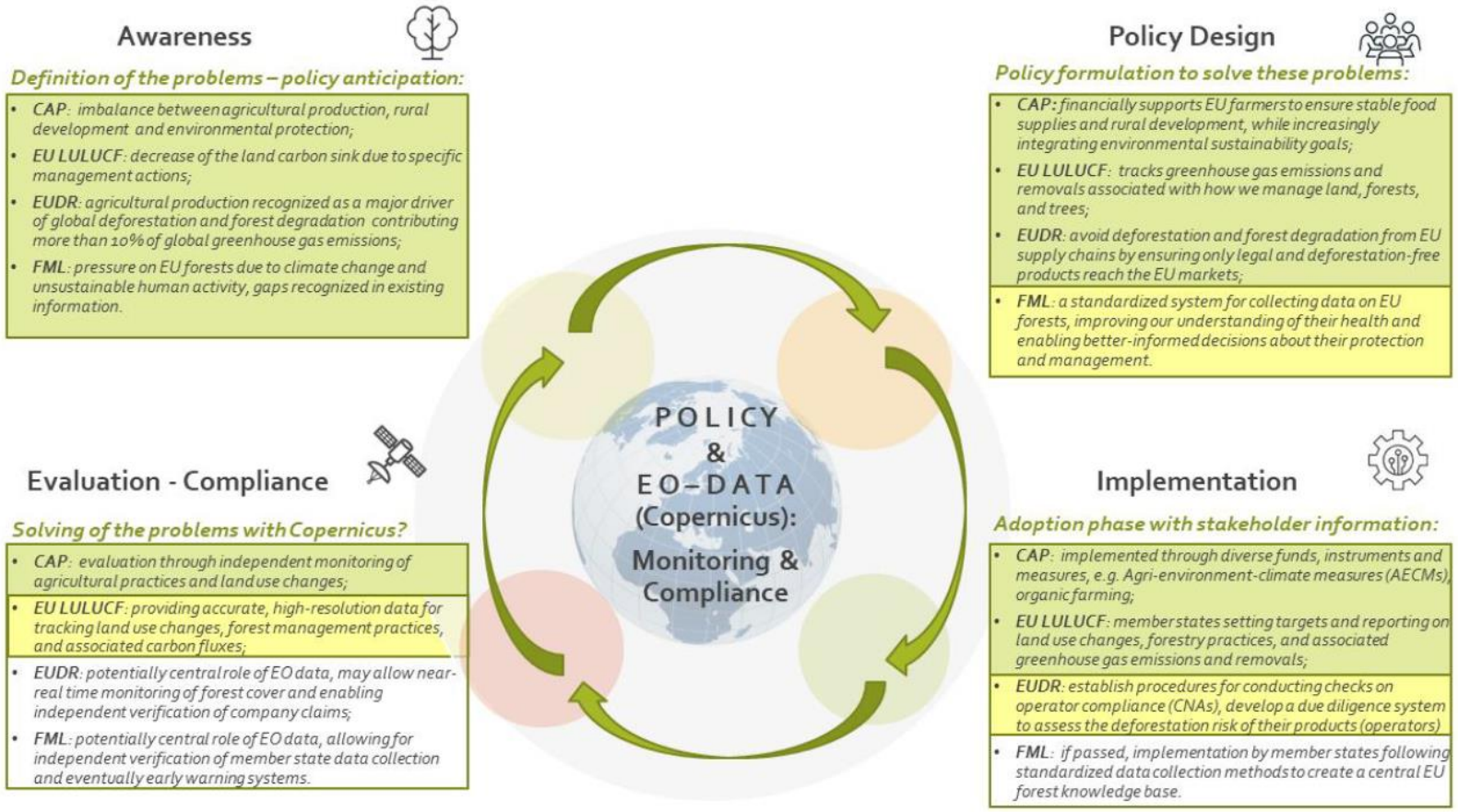
Recent EU policies requiring EO data

- Stimulates varying sustainable/climate-smart forest/ land management, land use and resource use practices
- Earth Observation becoming essential for policy making, compliance monitoring, transparency and enforcement
- Underpins data-driven environmental governance



Source: Berger et al., (2025): Evolving Earth observations for recent EU environmental policies, LUP

The right information for the right purpose



Source: Berger et al., (2025): Evolving Earth observations for recent EU environmental policies, LUP
https://doi.org/10.1016/j.landusepol.2025.107749

EC LULUCF regulation and implications for EO monitoring

1. Geographically-explicit land use conversion data:
   - Higher IPCC approaches and more transparency
2. Geographically-explicit information to identify priority areas that have the potential to contribute to climate action:
   - Spatial information for climate policy purposes
3. Improved monitoring of natural disturbances and impacts:
   - Identification (location, type, period) and potential compensation for losses
4. Moving towards IPCC Tier 2 as minimum requirement from 2028 onwards:
   - Tier 3 in specific areas (i.e. high carbon stocks, high climate risk)
5. Increasing timeliness for providing data and estimates:
   - Annual inventories, compliance checks, closer ties to policies and actions

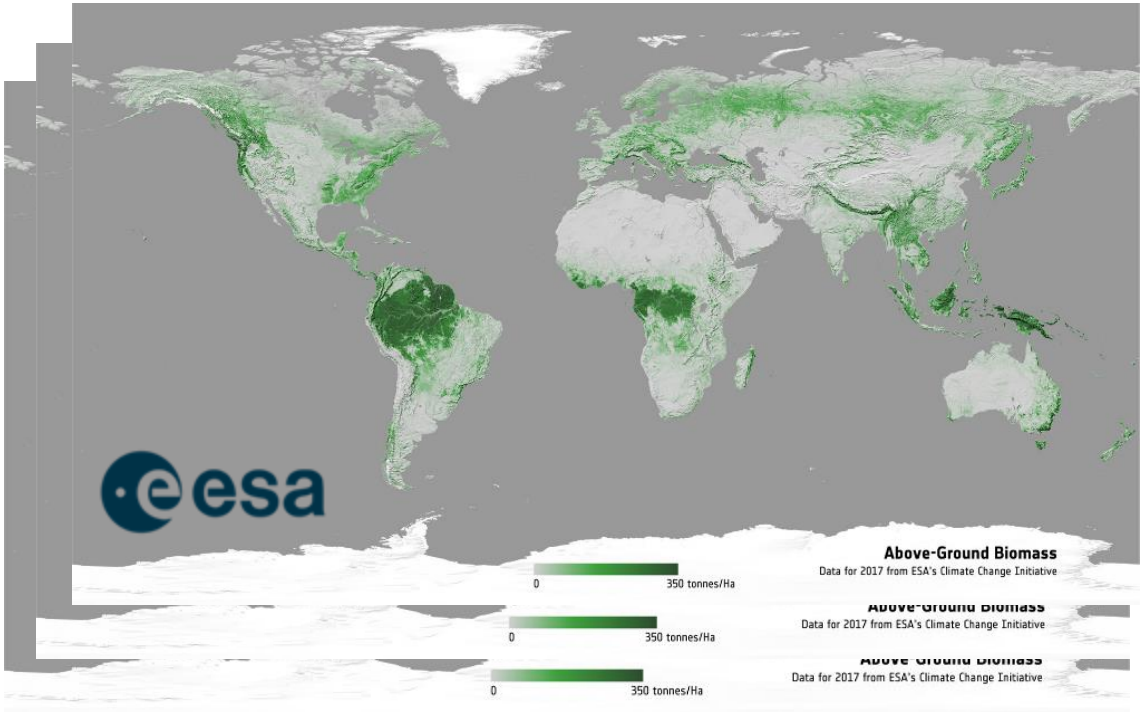
LULUCF regulation (2023): http://data.europa.eu/eli/reg/2023/839/oj

Berger et al., (2025): Evolving Earth observations for recent EU environmental policies, https://doi.org/10.1016/j.landusepol.2025.107749

CRCF requirements (related EO data)

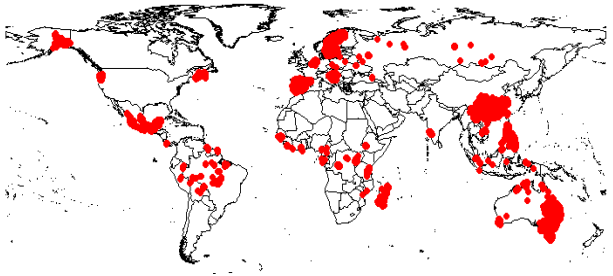
- Focus is on carbon removals related to “activities”
- For aboveground biomass: agroforestry and planting of trees - mostly lower biomass ranges and (small) annual increments
- Different methodological approaches: models, on-site measurements, remote sensing etc. (incl. combination)
- Long-term monitoring:
  - Eligibility criteria, incl. prior land use
  - Activity period and monitoring period (up to 40 years)
- Remote sensing: high-resolution (i.e. 10 m resolution), different sources (satellite, airborne LIDAR etc.)
- Relevance for risk assessment (i.e. reversals, permanence, buffer)

Aboveground biomass mapping from space

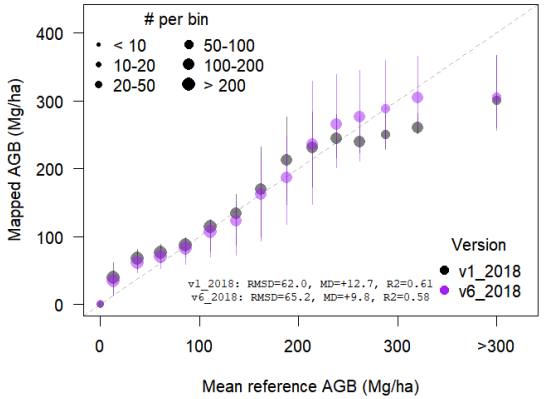


Products/ satellite	Start time	Resolution	Open Access
ESA CCI biomass V6	2007, 2010, 2015 - 2022	100m	✅
ESA Forest Carbon v2	2015-2022	20m	✅

Global reference database (~109.000 plots)



Santoro et al. 2021, 2024 *Global aboveground biomass for 2010, 2015-2022 at 100m spatial resolution. http://cci.esa.int/biomass, ESSD https://doi.org/10.1016/j.srs.2024.100169 Science of RS*



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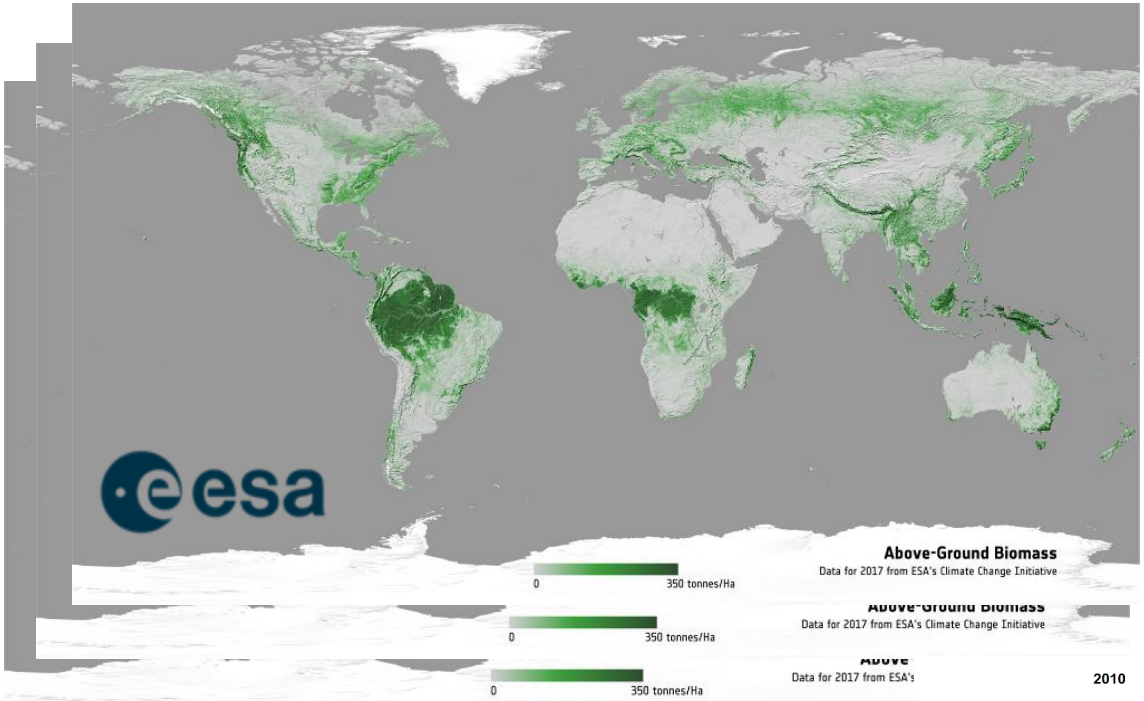

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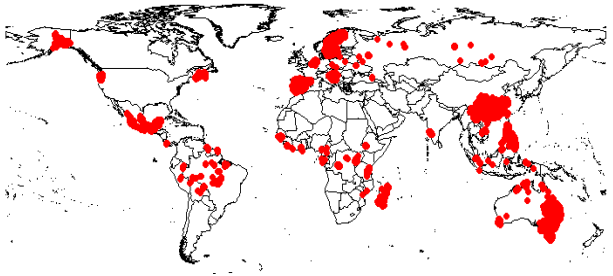

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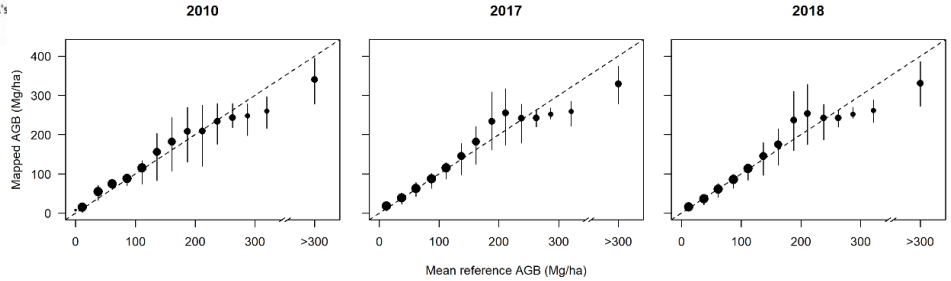
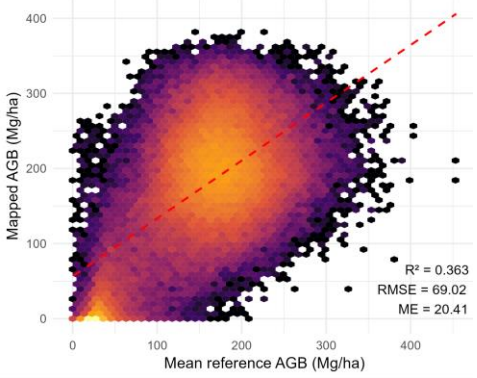
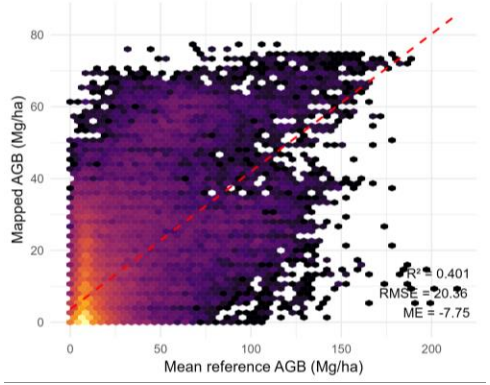


ESA forest carbon monitoring: European maps (20 m)

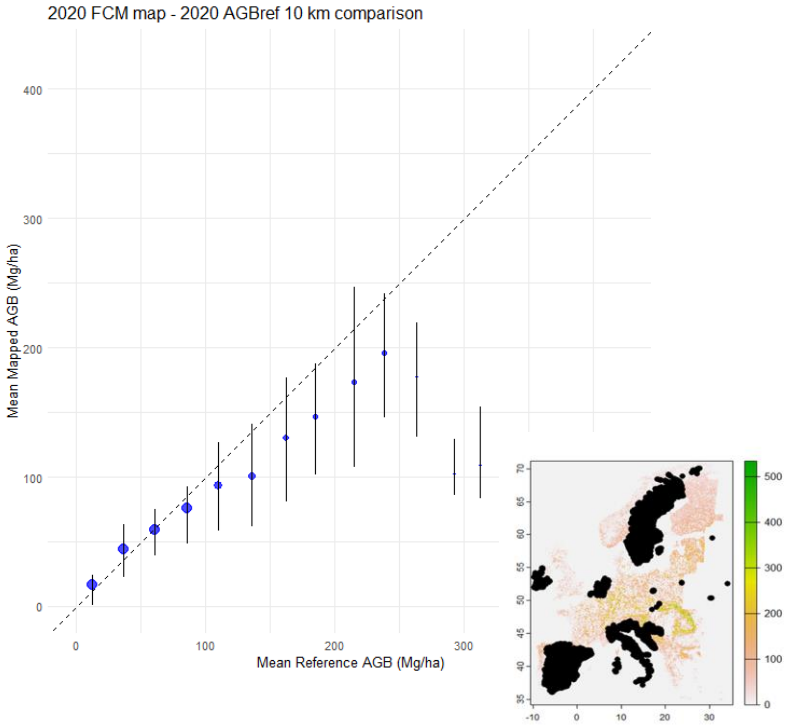
Validation for Poland, pixel-level



Validation for Spain, pixel-level



European-wide, aggregate level – 10km



Comparison with several independent NFI and LIDAR datasets

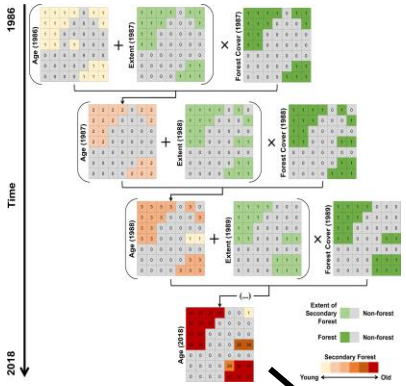
On the use of available space-based biomass maps

- Important improvements over recent years: time, detail, quality
- Results from independent validation:
  - Reasonable uncertainties (only) for aggregate estimates
  - Pixel-level uncertainties remain high (link to activities!)
  - Having RS biomass time series does not mean we can estimate changes with confidence
- Opportunities for space for time approaches at aggregate levels (see also presentation of Viola Heinrich, breakout session)
- Enhancing detail and quality for C-stock estimation (see also presentation of M. Migliavacca and I. Wheeler, various posters)

Satellite data for carbon accumulation (at aggregate levels)

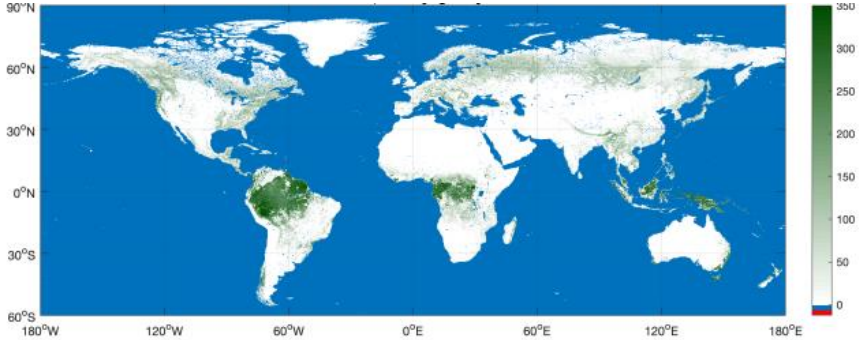
Time

Map of activities and time

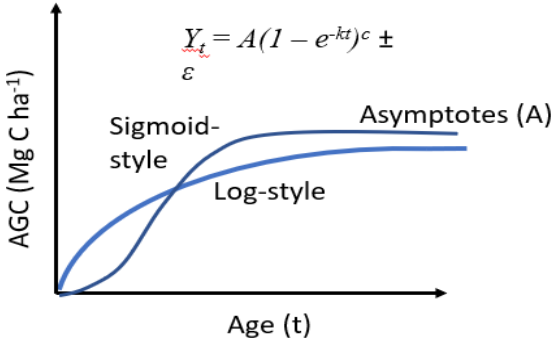


Space

Map of Aboveground Carbon, ESA-CCI

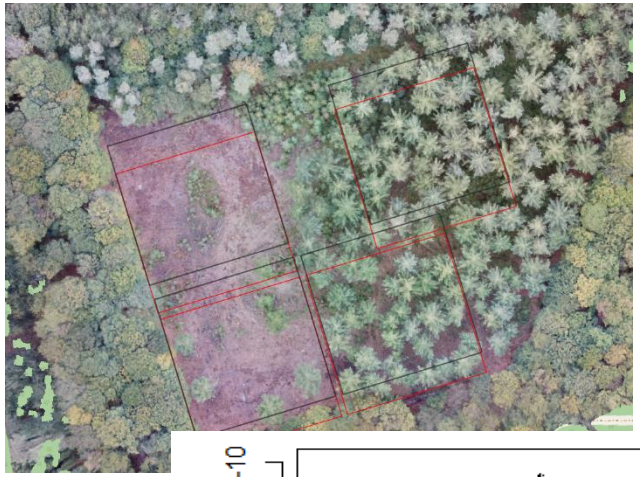


Space for time substitution

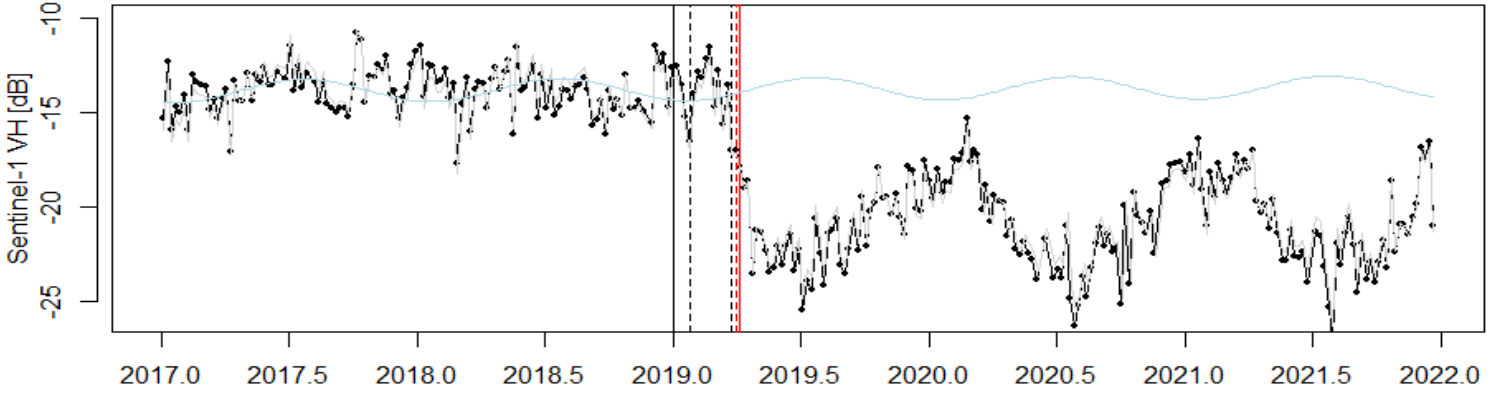


Courtesy of V. Heinrich

Increasing temporal detail in disturbance monitoring and characterization

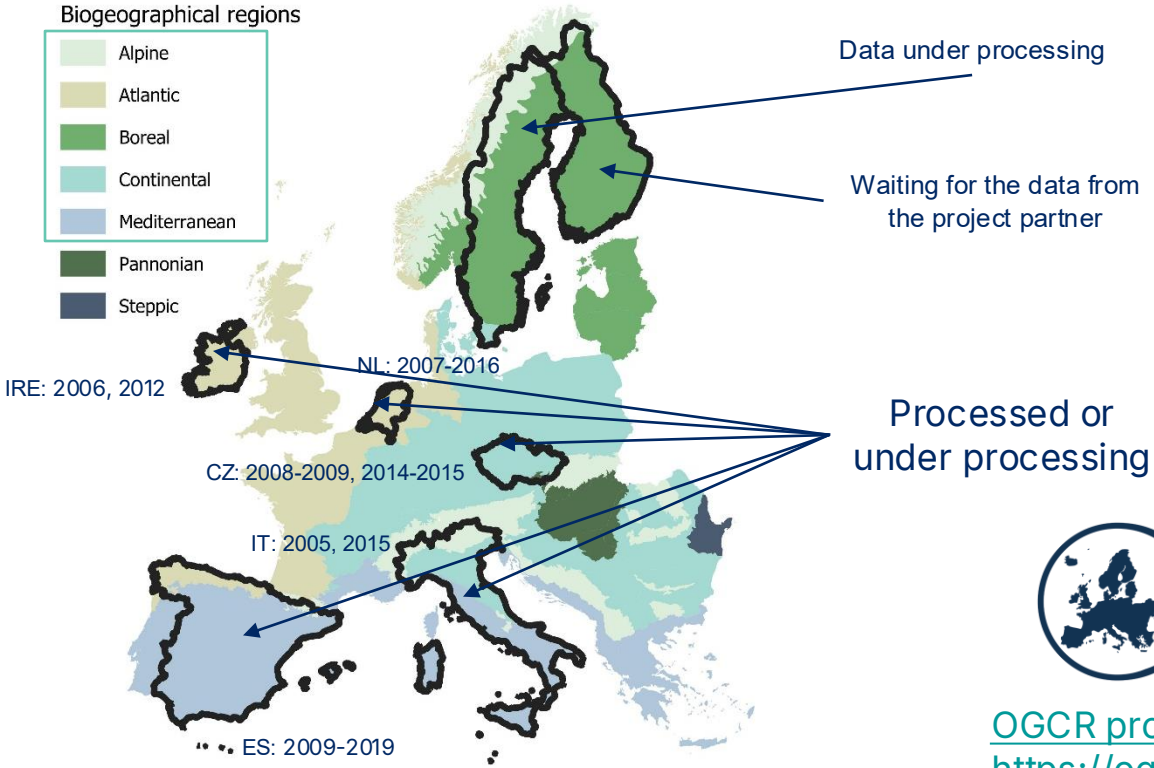


- Importance of dense time series data for tracking changes and dynamics (S1 2-3 days repeat for most of Europe)
- Potential for rapid detection of changes and tracking of forest and land use/management



Vd Woude et al., 2024: Sensitivity of Sentinel-1 Backscatter to Management-Related Disturbances in Temperate Forests

Making use Airborne Laser Scanning data overlapping with National Forest Inventories

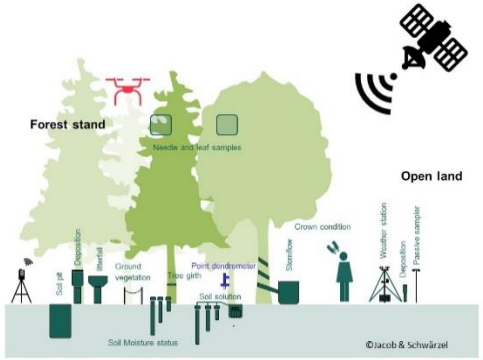


OGCR project
https://ogcr.eu/

Courtesy of Q. Song

* The biogeographical regions map is acquired from https://www.eea.europa.eu/en/analysis/maps-and-charts/biogeographical-regions-in-europe-2.

Linking ground- & space-based monitoring



Supersite monitoring concept
EC projects: FORWARDS / REMOTREE

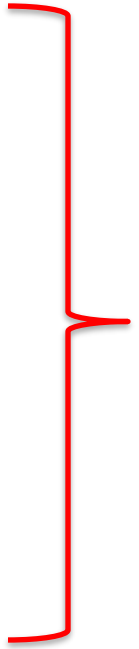
Restauration supersites (FORWARDS)

- Many EU countries run national forest inventories
- Expanding measurements and need for supersites to measure impact of different CRCF activities
- Developing and integrating complementary data streams:
  - New technologies
  - Systematic measurements at scale

EC FORWARDS: https://forwards-project.eu/
EC RemoTree: https://www.remotrees.eu

Integrating different observations for CRCF

Type of observation/ dataset	Advantages	Disadvantages
Satellite Earth Observations	EU-wide, long-term, high-resolution time series (activities, biomass ...)	Current uncertainties in carbon estimation at level of pixel (10 m!) and activities
Airborne Laser scanning	Good availability for EU, proven quality for biomass estimation (if properly calibrated)	Varying availability and quality across Europe Limited, systematic use for woody biomass (processing, calibration ...)
Ground-based inventories / NFIs	High-quality measurements of biomass stocks and changes in member states	Availability and quality varies across Europe Limited coverage for CRCF activities (i.e. forest areas)



Combine the advantages for estimation

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Earth observations for aboveground carbon estimation

- Methodological framework for CRCF: focus is on carbon removals related to “activities”
- Need to invest in measurements
- Opportunities in combining satellite time series, airborne LIDAR and ground-based inventories
- Delineation of activity areas and characteristics very important

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Thanks you