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Forests, Science and People

4.02.00 - FOREST RESOURCES INVENTORY AND MONITORING

# Latest developments in the field of remote sensing and forest monitoring

Prof. Gherardo Chirici
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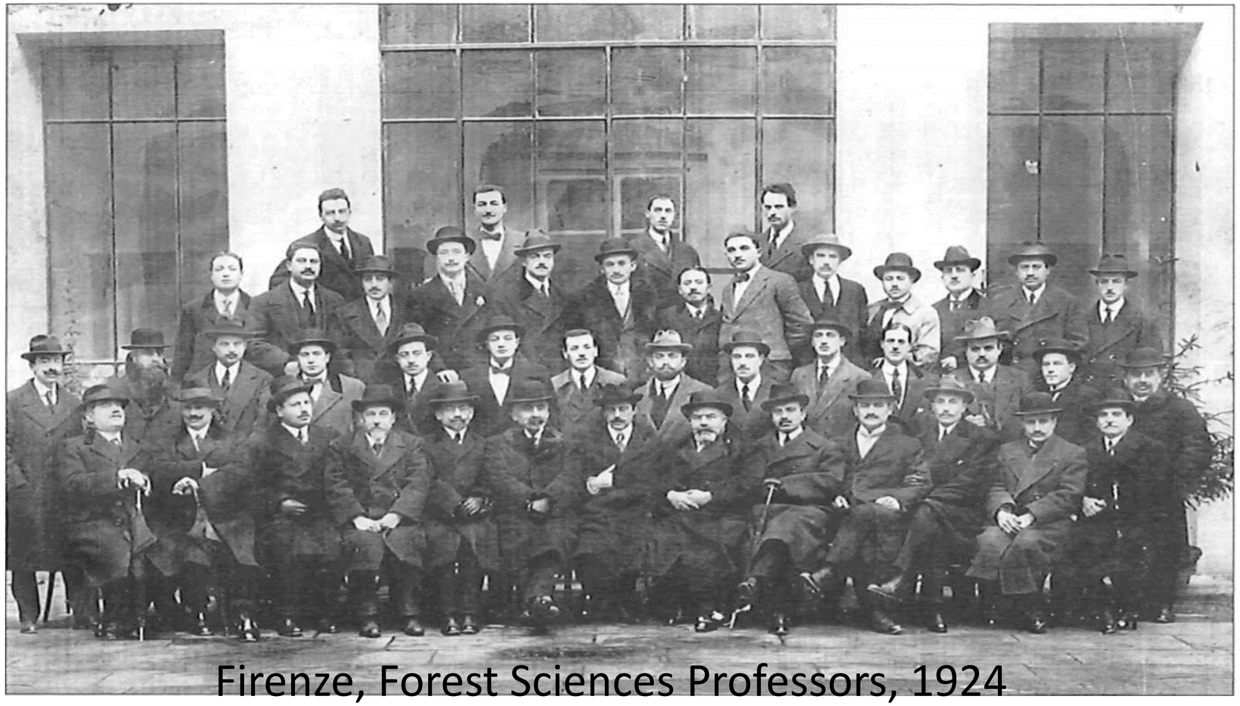
geo LAB
Laboratory of Forest Geomatics

- **15** Universities in Italy have forestry programmes
- The first one was at the University of Florence since **1869**, until **1982** it was the only one



Firenze, Forest Sciences Professors, 1924

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Traditional National Forest Inventories (NFIs) use a design based approach to infer statistics over **LARGE** areas from field measures acquired in a **VERY SMALL** sample (approx 0.001%) of the forest area

# 1st century of NFIs

**REMOTE SENSING** was used in NFIs since the very beginning with traditional aerial photography

From NFIs to
**Enhanced Forest Inventories**
Sensu White et al. (2016)

Erkki Tomppo • Thomas Gschwantner •
Mark Lawrence • Ronald E. McRoberts
Editors

National Forest Inventories

Pathways for Common Reporting

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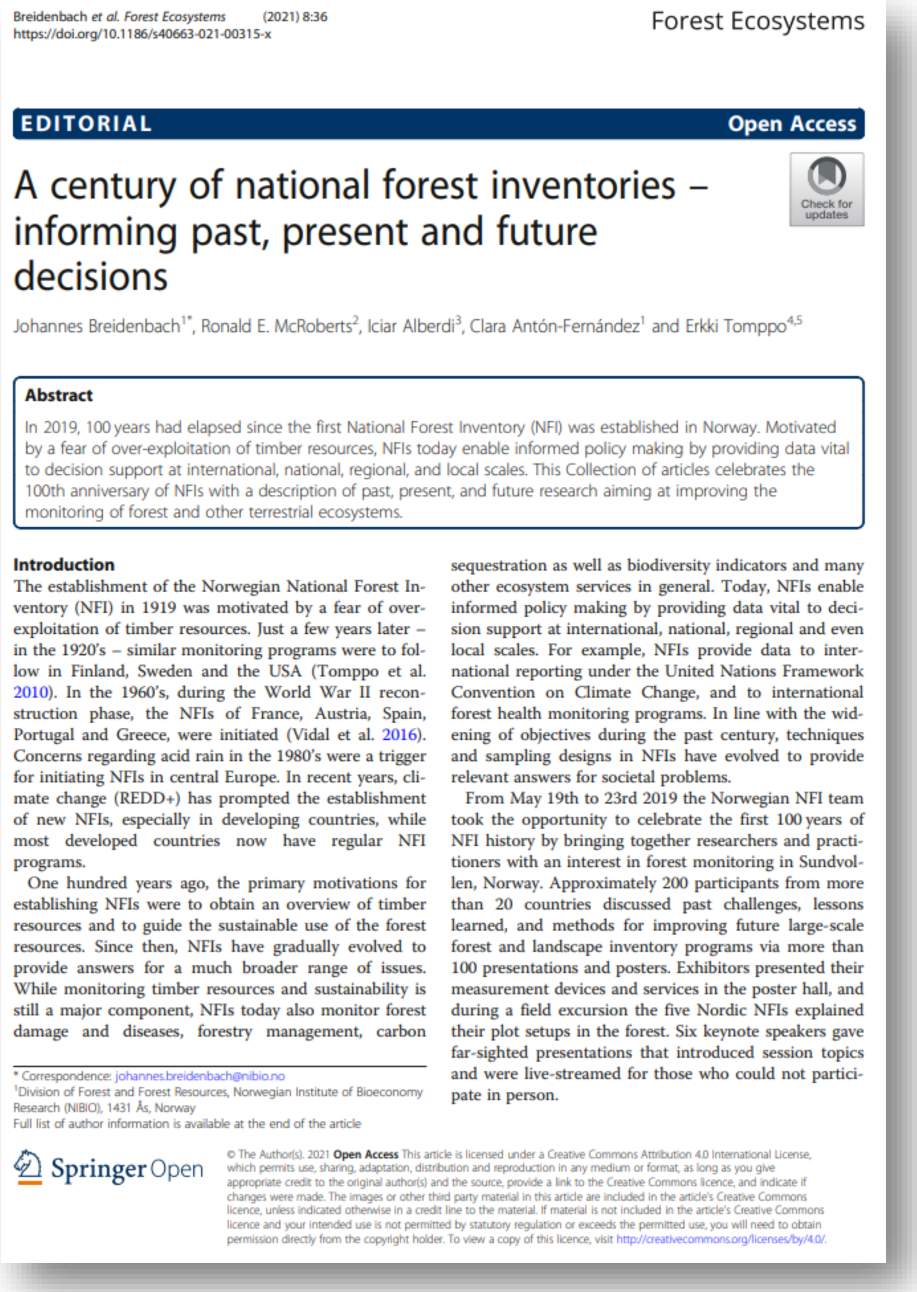

Breidenbach *et al. Forest Ecosystems* (2021) 8:36
https://doi.org/10.1186/s40663-021-00315-x

Forest Ecosystems

**EDITORIAL** **Open Access**

## A century of national forest inventories – informing past, present and future decisions

Johannes Breidenbach[1*], Ronald E. McRoberts[2], Iciar Alberdi[3], Clara Antón-Fernández[1] and Erkki Tomppo[4,5]

**Abstract**

In 2019, 100 years had elapsed since the first National Forest Inventory (NFI) was established in Norway. Motivated by a fear of over-exploitation of timber resources, NFIs today enable informed policy making by providing data vital to decision support at international, national, regional, and local scales. This Collection of articles celebrates the 100th anniversary of NFIs with a description of past, present, and future research aiming at improving the monitoring of forest and other terrestrial ecosystems.

**Introduction**

The establishment of the Norwegian National Forest Inventory (NFI) in 1919 was motivated by a fear of over-exploitation of timber resources. Just a few years later – in the 1920's – similar monitoring programs were to follow in Finland, Sweden and the USA (Tomppo et al. 2010). In the 1960's, during the World War II reconstruction phase, the NFIs of France, Austria, Spain, Portugal and Greece, were initiated (Vidal et al. 2016). Concerns regarding acid rain in the 1980's were a trigger for initiating NFIs in central Europe. In recent years, climate change (REDD+) has prompted the establishment of new NFIs, especially in developing countries, while most developed countries now have regular NFI programs.

One hundred years ago, the primary motivations for establishing NFIs were to obtain an overview of timber resources and to guide the sustainable use of the forest resources. Since then, NFIs have gradually evolved to provide answers for a much broader range of issues. While monitoring timber resources and sustainability is still a major component, NFIs today also monitor forest damage and diseases, forestry management, carbon sequestration as well as biodiversity indicators and many other ecosystem services in general. Today, NFIs enable informed policy making by providing data vital to decision support at international, national, regional and even local scales. For example, NFIs provide data to international reporting under the United Nations Framework Convention on Climate Change, and to international forest health monitoring programs. In line with the widening of objectives during the past century, techniques and sampling designs in NFIs have evolved to provide relevant answers for societal problems.

From May 19th to 23rd 2019 the Norwegian NFI team took the opportunity to celebrate the first 100 years of NFI history by bringing together researchers and practitioners with an interest in forest monitoring in Sundvollen, Norway. Approximately 200 participants from more than 20 countries discussed past challenges, lessons learned, and methods for improving future large-scale forest and landscape inventory programs via more than 100 presentations and posters. Exhibitors presented their measurement devices and services in the poster hall, and during a field excursion the five Nordic NFIs explained their plot setups in the forest. Six keynote speakers gave far-sighted presentations that introduced session topics and were live-streamed for those who could not participate in person.

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Full list of author information is available at the end of the article

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# In NFIs Remote sensing contributed:

- To the production of more timely, cost efficient, and precise **traditional inventory estimates**

- To derive **new spatial products** (maps, small area estimates)

**Technologies** that are now on the horizon have the potential to alter radically the ways in which trees are measured,estimates are produced, and products are delivered.

The **lack** of standardized, spatially exhaustive **open access datasets**, as well as community consensus on methods and best practices limits the broader uptake and operationalization of these approaches

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ScienceDirect
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www.elsevier.com/locate/rse

Remote sensing support for national forest inventories

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*Scandinavian Journal of Forest Research*, 2010; 25: 368–381
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**REVIEW ARTICLE**

**Advances and emerging issues in national forest inventories**

RONALD E. McROBERTS[1], ERKKI O. TOMPPO[2] & ERIK NÆSSET[3]

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**Remote Sensing Technologies for Enhancing Forest Inventories: A Review**

**Joanne C. White[1,*], Nicholas C. Coops[2], Michael A. Wulder[1], Mikko Vastaranta[3], Thomas Hilker[4], and Piotr Tompalski[2]**

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Modelling lidar-derived estimates of forest attributes over space and time: A review of approaches and future trends

Nicholas C. Coops[a,*], Piotr Tompalski[a], Tristan R.H. Goodbody[a], Martin Queinnec[a], Joan E. Luther[b], Douglas K. Bolton[c], Joanne C. White[d], Michael A. Wulder[d], Oliver R. van Lier[e], Txomin Hermosilla[d]

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Large area
Airborne lidar
Spaceborne lidar
GEDI
ICESat

ABSTRACT

Light detection and ranging (lidar) data acquired from airborne or spaceborne platforms have revolutionized measurement and mapping of forest attributes. Airborne data are often either acquired using multiple overlapped flight lines to provide complete coverage of an area of interest, or using transects to sample a given population. Spaceborne lidar datasets are unique to each sensor and are sample- or profile-based with characteristics driven by acquisition mode and orbital parameters. To leverage the wealth of accurate vegetation structural data from these lidar systems, a number of approaches have been developed to extend these observations over broader areas, from local landscapes to the globe. In this review we examine studies that have utilised modelling approaches to extend air- or space-based lidar data with the aim of communicating methods, outcomes, and accuracies, and offering guidance on linking lidar metrics and lidar-derived forest attributes with broad-area predictors. Modelling approaches are developed for a variety of applications. In some cases, generation of spatially-exhaustive layers may be useful for forest management purposes, driving management and inventory decisions over smaller focus areas or regions. In other cases, outputs are designed for monitoring at regional or global scales, and may be – due to the spatial grain of the structural estimates – insufficiently accurate or reliable for management. From the reviewed studies, we found height, aboveground biomass and volume, derived from either upper proportions of a large-footprint full-waveform lidar profiles, or statistically modelled from discrete return small-footprint lidar point clouds, to be the most commonly extended forest attributes, followed by canopy cover, basal area and stand complexity. Assessment of the accuracy and bias of the extrapolated forest attributes varied with both independent and model-derived estimates. The coefficient of determination ($R^2$) was the most often reported, followed by absolute and relative (i.e., as a proportion of the mean) root mean square error (RMSE and RMSE% respectively). Compilation of the stated accuracies suggested that the variance explained in predictions of forest height ranged from $R^2 = 0.38$ to 0.90 (mean = 0.64), RMSE from 2 to 6m and RMSE% from 12 to 34%. For volume, $R^2$ ranged from 0.25 to 0.72 (mean = 0.53) and RMSE from 60 to 87 $m^3$/ha and for aboveground biomass (AGB) $R^2$ ranged from 0.35 to 0.78 (mean = 0.55) and RMSE from 28 to 44 Mg/ha. There was no consensus on the level of accuracy required to support successful extension over larger areas. Ultimately, the review suggests that the information need motivating the spatial extension over larger areas drives the choice of the type of lidar data, spatial datasets and related grain. We conclude by discussing future directions and the outlook for new approaches including new lidar-derived response variables, advances in modelling approaches, and assessment of change.

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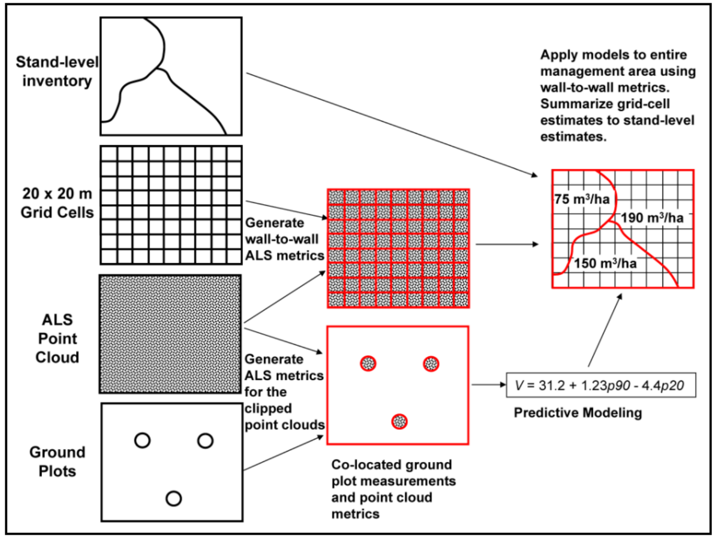
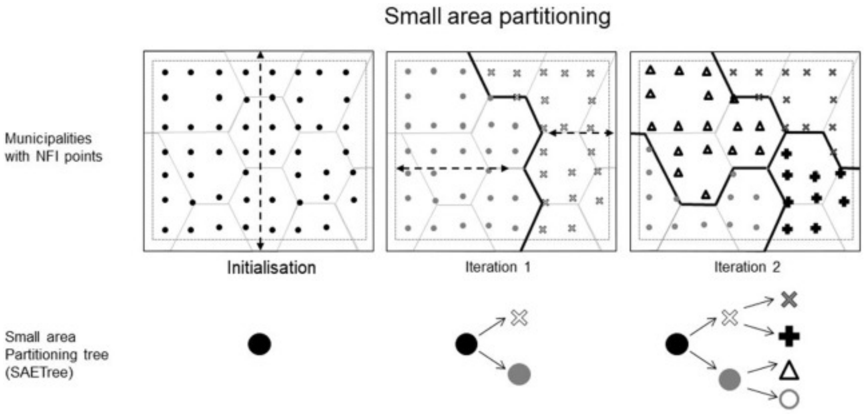
# Data assimilation/data integration

How to integrate multiple input data from multiple sources?

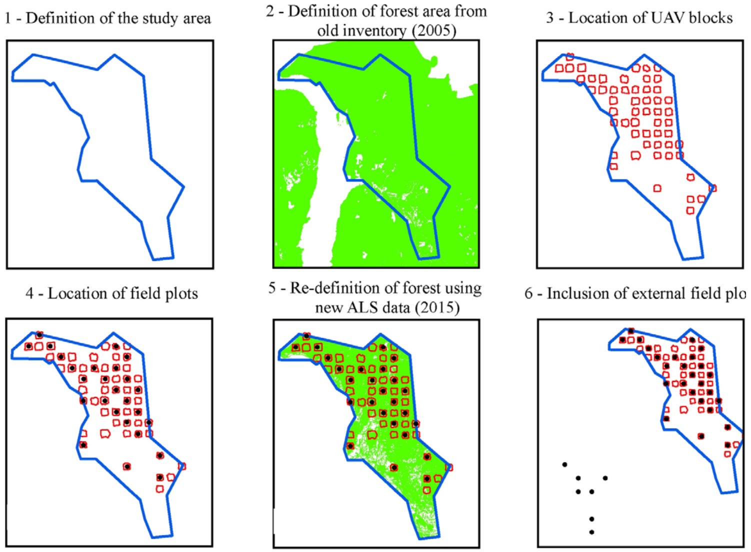
We just have to choice!



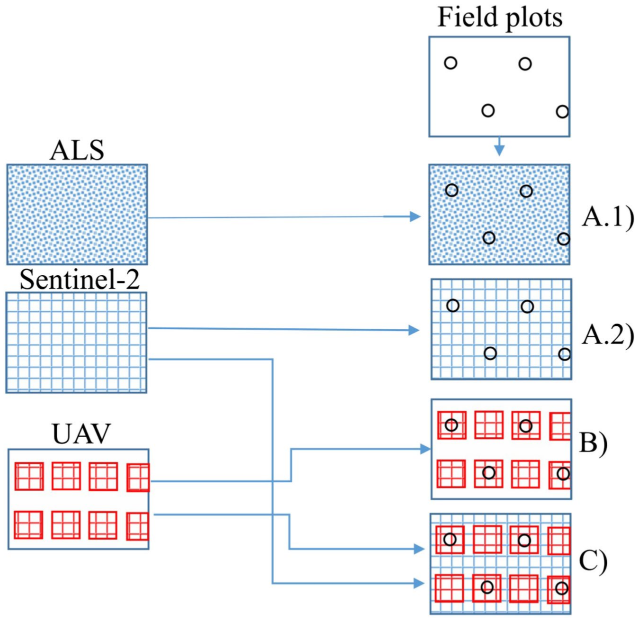
White et al., 2013. The Utility of Image-Based Point Clouds for Forest Inventory: A Comparison with Airborne Laser Scanning. https://doi.org/10.3390/f4030518



Vega et al., 2021
A new small area estimation algorithm to balance between statistical precision and scale
https://doi.org/10.1016/j.jag.2021.102303



Puliti et al., 2017
Use of partial-coverage UAV data in sampling for large scale forest inventories.
https://doi.org/10.1016/j.rse.2017.03.019



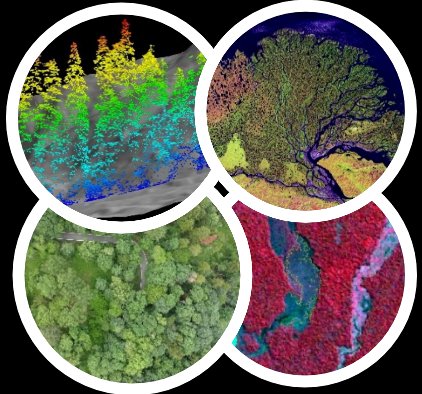
Puliti S, Saarela S, et al., 2018
Combining UAV and Sentinel-2 auxiliary data for forest growing stock volume estimation through hierarchical model-based inference
https://doi.org/10.1016/j.rse.2017.10.007

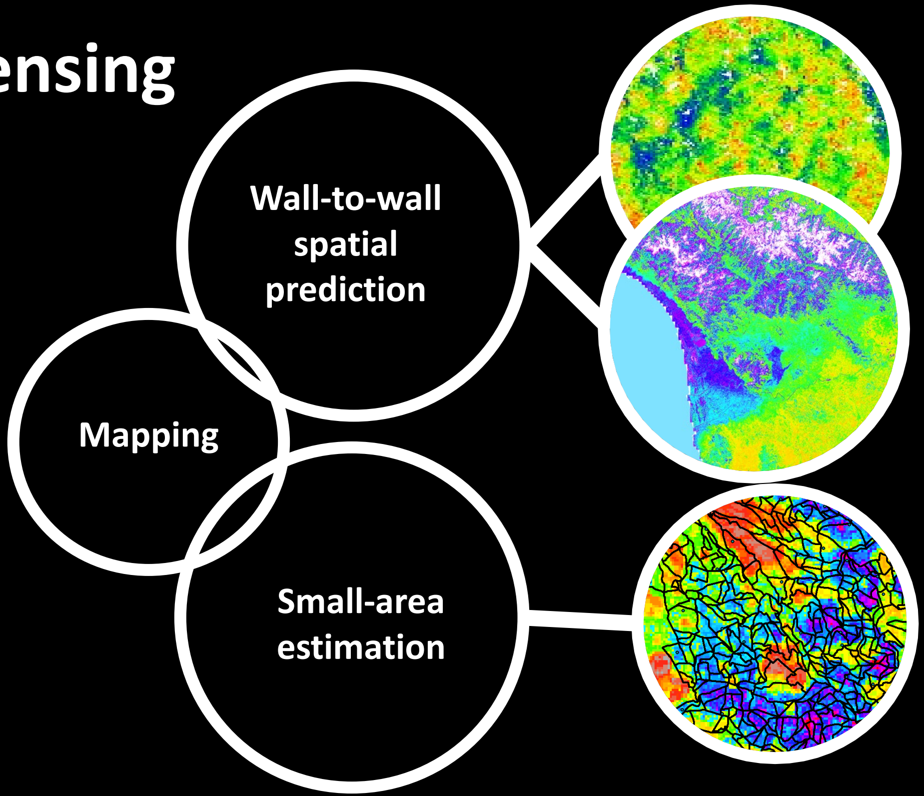
# Integrating NFI with remote sensing

National Forest Inventory sampling data

+

Remote Sensing data





**Important to monitor, measure and manage**

Wood production

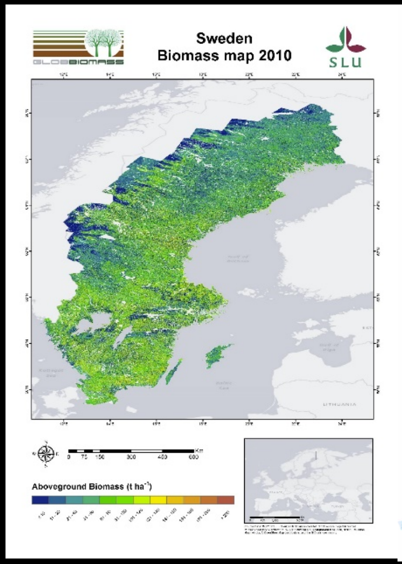
Biodiversity

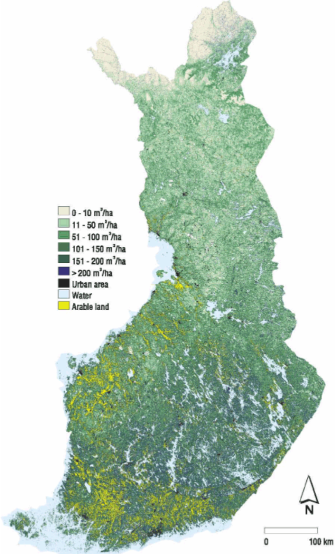
Carbon Stock

Social benefits

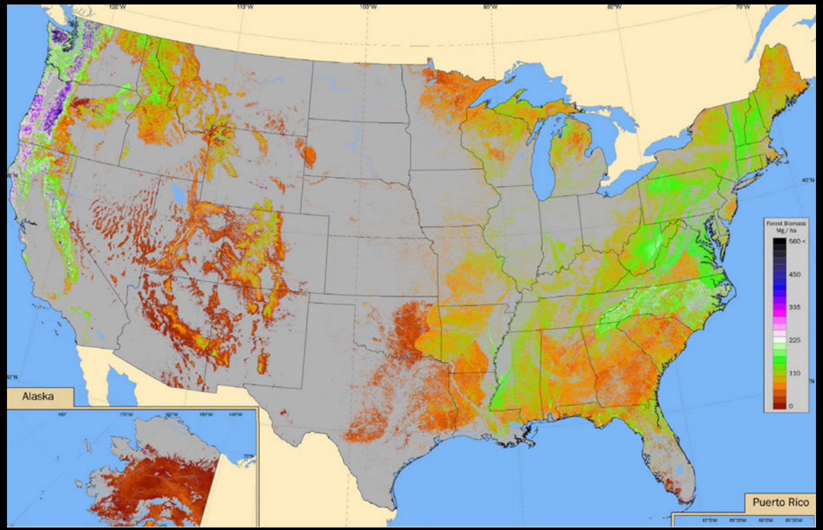
**Examples**

http://www.slu.se/skogskarta/





https://www.fia.fs.fed.us/



# New opportunities from Earth Observation

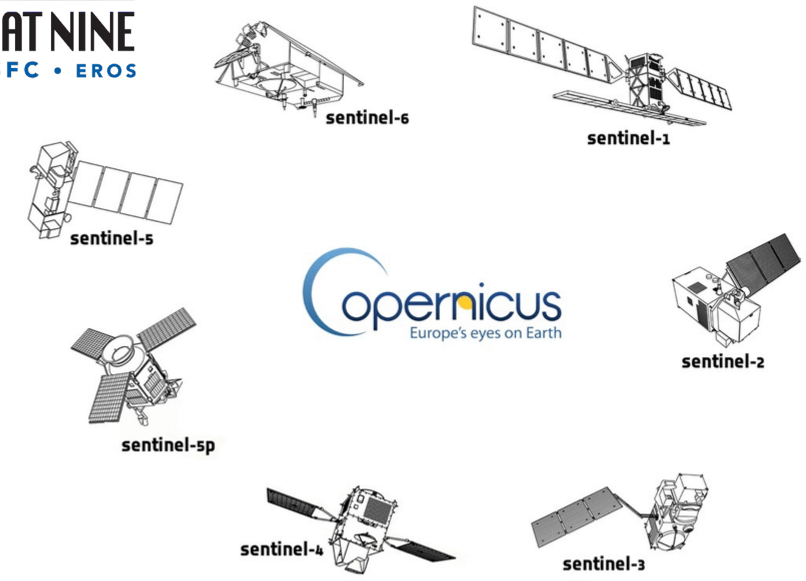
- **Increasing number** of high resolution multispectral optical and radar **platforms** (Sentinels, Landsat)
- New **LiDAR** data (ICESAT, GEDI, TLS, UAV)
- Incresing number of spatial remotely sensed based data at **COPERNICUS**
- New high resolution small satellites platforms (PLANET), **real time** monitoring
- New **hyperspectral** platforms (PRISMA)
- **UAV** and digital photogrammetry (SFM)

GEDI
ECOSYSTEM LIDAR

copernicus
Europe's eyes on Earth

esa
European Space Agency

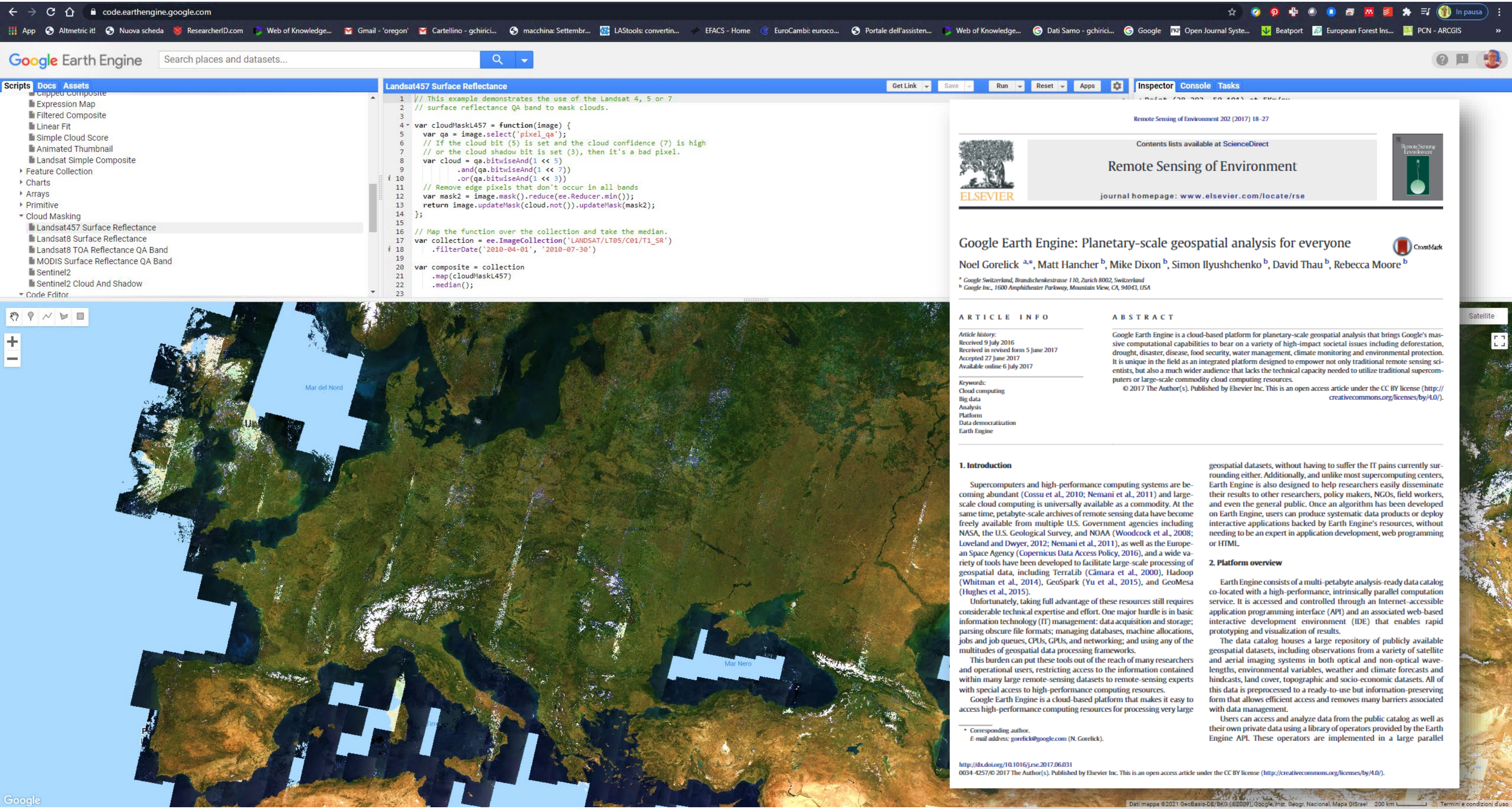
NASA • USGS
LANDSAT NINE
KSC • GSFC • EROS



planet.
See Change.
Change the World.

PRISMA
ASI AGENZIA SPAZIALE ITALIANA
LEONARDO
OHB ITALIA

# Colocated Data + Computation + APIs



```
// This example demonstrates the use of the Landsat 4, 5 or 7
// surface reflectance QA band to mask clouds.

var cloudMaskL457 = function(image) {
  var qa = image.select('pixel_qa');
  // If the cloud bit (5) is set and the cloud confidence (7) is high
  // or the cloud shadow bit is set (3), then it's a bad pixel.
  var cloud = qa.bitwiseAnd(1 << 5)
          .and(qa.bitwiseAnd(1 << 7))
          .or(qa.bitwiseAnd(1 << 3))
  // Remove edge pixels that don't occur in all bands
  var mask2 = image.mask().reduce(ee.Reducer.min());
  return image.updateMask(cloud.not()).updateMask(mask2);
};

// Map the function over the collection and take the median.
var collection = ee.ImageCollection('LANDSAT/LT05/C01/T1_SR')
    .filterDate('2010-04-01', '2010-07-30')

var composite = collection
    .map(cloudMaskL457)
    .median();

```

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# Google Earth Engine: Planetary-scale geospatial analysis for everyone

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ABSTRACT

Google Earth Engine is a cloud-based platform for planetary-scale geospatial analysis that brings Google's massive computational capabilities to bear on a variety of high-impact societal issues including deforestation, drought, disaster, disease, food security, water management, climate monitoring and environmental protection. It is unique in the field as an integrated platform designed to empower not only traditional remote sensing scientists, but also a much wider audience that lacks the technical capacity needed to utilize traditional supercomputers or large-scale commodity cloud computing resources.

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## 1. Introduction

Supercomputers and high-performance computing systems are becoming abundant (Cossu et al., 2010; Nemani et al., 2011) and large-scale cloud computing is universally available as a commodity. At the same time, petabyte-scale archives of remote sensing data have become freely available from multiple U.S. Government agencies including NASA, the U.S. Geological Survey, and NOAA (Woodcock et al., 2008; Loveland and Dwyer, 2012; Nemani et al., 2011), as well as the European Space Agency (Copernicus Data Access Policy, 2016), and a wide variety of tools have been developed to facilitate large-scale processing of geospatial data, including TerraLib (Câmara et al., 2000), Hadoop (Whitman et al., 2014), GeoSpark (Yu et al., 2015), and GeoMesa (Hughes et al., 2015).

Unfortunately, taking full advantage of these resources still requires considerable technical expertise and effort. One major hurdle is in basic information technology (IT) management: data acquisition and storage; parsing obscure file formats; managing databases, machine allocations, jobs and job queues, CPUs, GPUs, and networking; and using any of the multitudes of geospatial data processing frameworks.

This burden can put these tools out of the reach of many researchers and operational users, restricting access to the information contained within many large remote-sensing datasets to remote-sensing experts with special access to high-performance computing resources.

Google Earth Engine is a cloud-based platform that makes it easy to access high-performance computing resources for processing very large geospatial datasets, without having to suffer the IT pains currently surrounding either. Additionally, and unlike most supercomputing centers, Earth Engine is also designed to help researchers easily disseminate their results to other researchers, policy makers, NGOs, field workers, and even the general public. Once an algorithm has been developed on Earth Engine, users can produce systematic data products or deploy interactive applications backed by Earth Engine's resources, without needing to be an expert in application development, web programming or HTML.

## 2. Platform overview

Earth Engine consists of a multi-petabyte analysis-ready data catalog co-located with a high-performance, intrinsically parallel computation service. It is accessed and controlled through an Internet-accessible application programming interface (API) and an associated web-based interactive development environment (IDE) that enables rapid prototyping and visualization of results.

The data catalog houses a large repository of publicly available geospatial datasets, including observations from a variety of satellite and aerial imaging systems in both optical and non-optical wavelengths, environmental variables, weather and climate forecasts and hindcasts, land cover, topographic and socio-economic datasets. All of this data is preprocessed to a ready-to-use but information-preserving form that allows efficient access and removes many barriers associated with data management.

Users can access and analyze data from the public catalog as well as their own private data using a library of operators provided by the Earth Engine API. These operators are implemented in a large parallel

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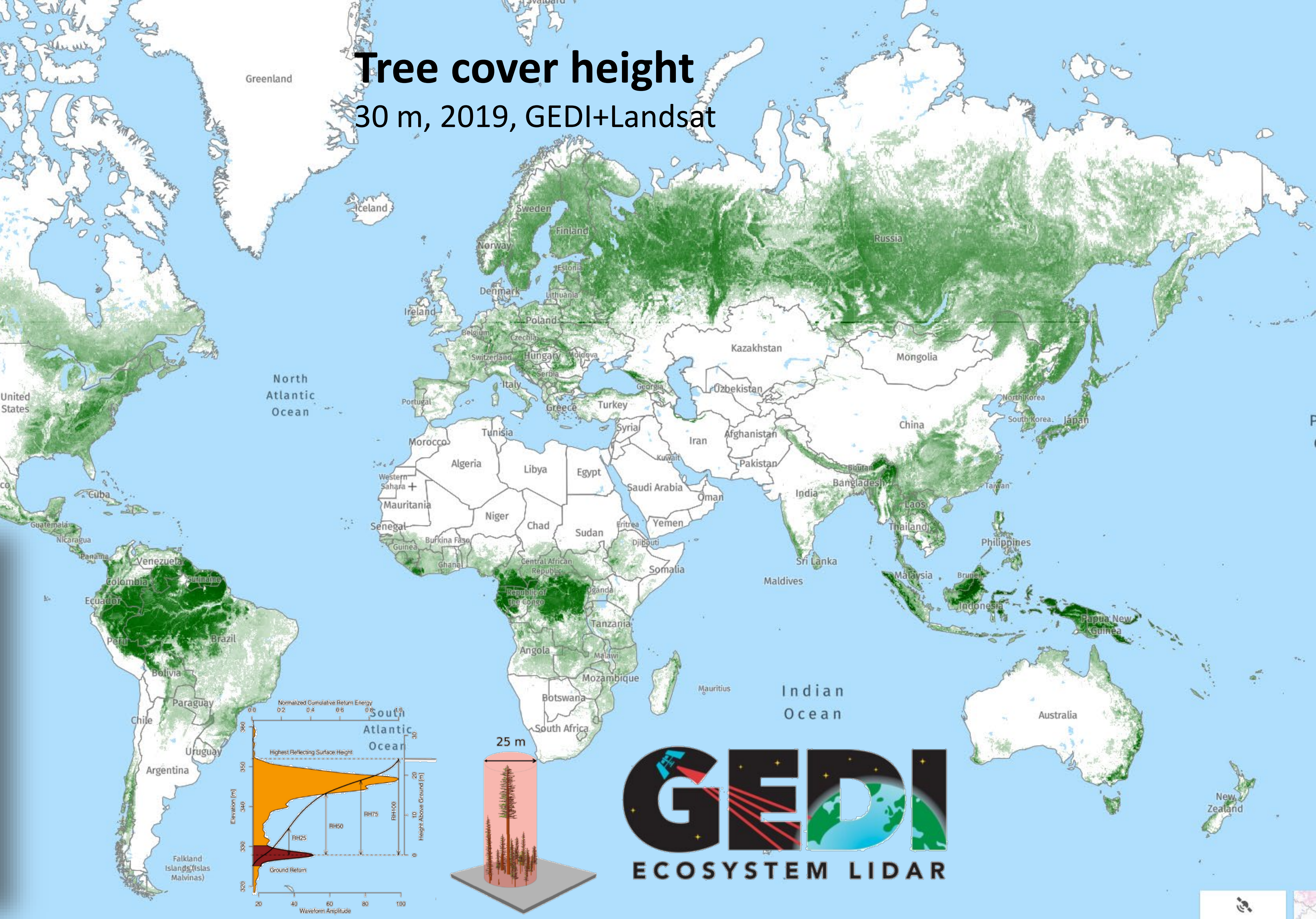
# Tree cover height

30 m, 2019, GEDI+Landsat



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## Mapping global forest canopy height through integration of GEDI and Landsat data

Peter Potapov[a,*], Xinyuan Li[a], Andres Hernandez-Serna[a], Alexandra Tyukavina[a], Matthew C. Hansen[a], Anil Kommareddy[a], Amy Pickens[a], Svetlana Turubanova[a], Hao Tang[a], Carlos Edibaldo Silva[a], John Armston[a], Ralph Dubayah[a], J. Bryan Blair[b], Michelle Hofton[a]

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ARTICLE INFO

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Forest height
Forest monitoring
Time-series

ABSTRACT

Consistent, large-scale operational monitoring of forest height is essential for estimating forest-related carbon emissions, analyzing forest degradation, and quantifying the effectiveness of forest restoration initiatives. The Global Ecosystem Dynamics Investigation (GEDI) lidar instrument onboard the International Space Station has been collecting unique data on vegetation structure since April 2019. Here, we employed global Landsat analysis-ready data to extrapolate GEDI footprint-level forest canopy height measurements, creating a 30 m spatial resolution global forest canopy height map for the year 2019. The global forest height map was compared to the GEDI validation data (RMSE = 6.6 m; MAE = 4.45 m, $R^2$ = 0.62) and available airborne lidar data (RMSE = 9.07 m; MAE = 6.36 m, $R^2$ = 0.61). The demonstrated integration of GEDI data with time-series optical imagery is expected to enable multidecadal historic analysis and operational forward monitoring of forest height and its dynamics. Such capability is important to support global climate and sustainable development initiatives.

### 1. Introduction

Forests (defined here as wildland, managed, and planted tree cover) perform essential ecosystem functions that sustain the Earth climate and biosphere and provide a wide array of ecosystem services. Forest ecosystems are functioning as the largest terrestrial carbon storage (Dixon et al., 1994) and sink (Pan et al., 2011). Forest regrowth (natural restoration and tree plantations) is responsible for more than 60% of the forest carbon sink (Pugh et al., 2019), while timber extraction and forest clearing for other land uses are among the largest sources of anthropogenic carbon emissions (Houghton, 1999). Forest restoration, avoiding forest conversion, and sustainable forest management are considered as cost-effective natural climate solutions in stabilizing climate and preventing species extinction (Balmford et al., 2002; Gibson et al., 2011; Griscom et al., 2017).

Spatially exhaustive, multitemporal data on global forest ecosystem structure are required for carbon accounting and parameterizing global-scale biogeochemistry, hydrology, biodiversity, and climate models. Such data are crucial for practical applications including carbon emissions and sequestration reporting, forest degradation assessment, and quantification of the effectiveness of forest restoration initiatives. Specifically, forest canopy height is used to estimate forest aboveground biomass and timber volume, to monitor the effects of forest degradation, to measure the success of forest restoration, and to model other key ecosystem variables such as primary production and biodiversity (Asner et al., 2012; Goetz and Dubayah, 2011). Traditionally, tree height has been measured in the field, and more recently, using Airborne Laser Scanning (ALS) systems. Both methods are expensive and impractical over large geographic extents. Satellite-based forest canopy height earth observation data have previously been limited to NASA GLAS (ICESat) and more recently to ATLAS (ICESat-2) lidar instruments (Lefsky, 2010; Simard et al., 2011; Popescu et al., 2018). However, these instruments are not optimized for vegetation mapping (Montesano et al., 2015; Hansen et al., 2016).

The NASA Global Ecosystem Dynamics Investigation (GEDI) is a new spaceborne lidar instrument operating onboard the International Space Station (ISS) and has been collecting data since April 2019 (Dubayah et al., 2020a). GEDI is a full waveform lidar specifically designed for

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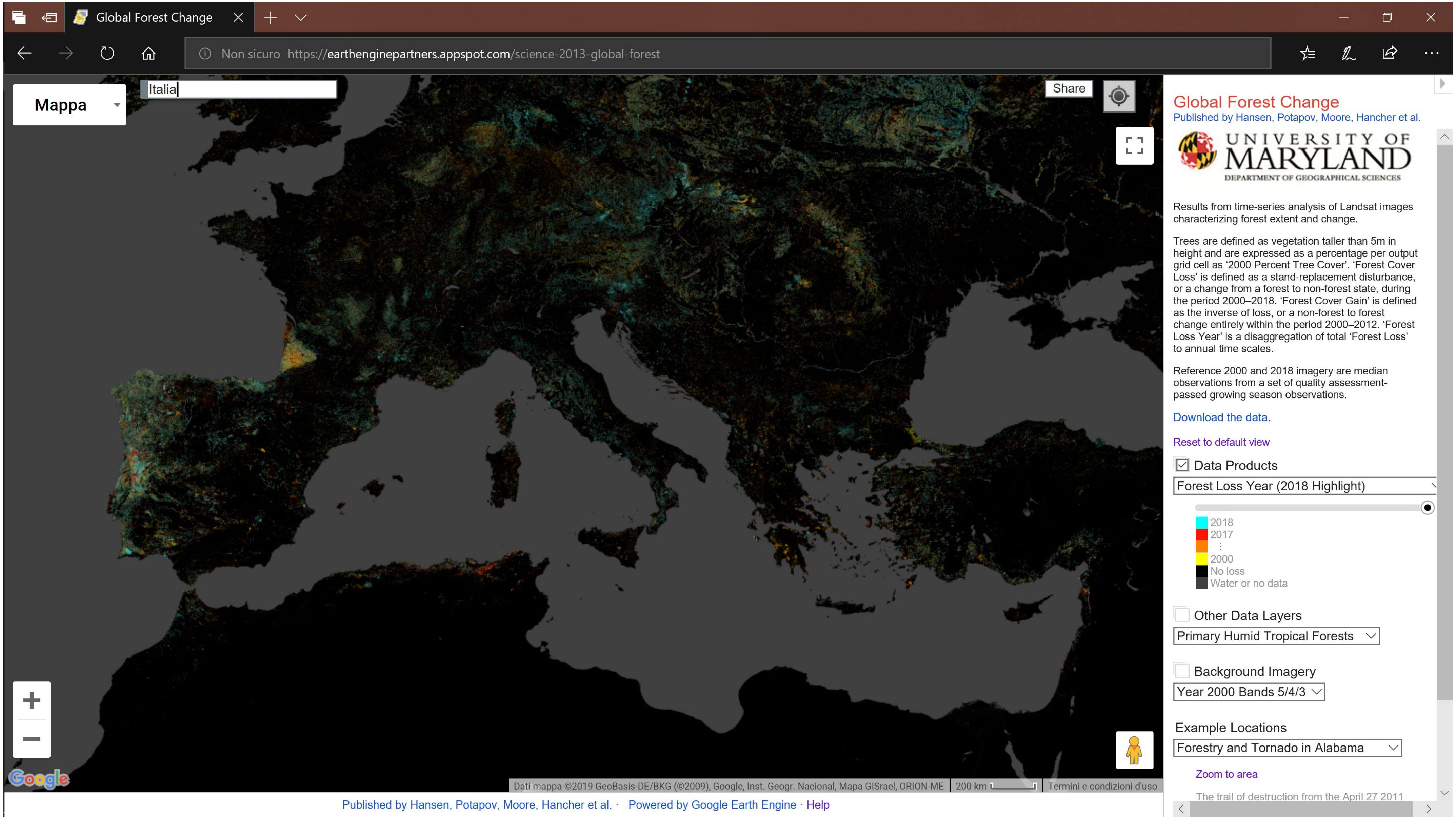
GEDI
ECOSYSTEM LIDAR

# Do we have to rely to Google and NASA in Europe too?

High-Resolution Global Maps of 21st-Century Forest Cover Change

**M. C. Hansen[1,*], P. V. Potapov[1], R. Moore[2], M. Hancher[2], S. A. Turubanova[1], A. Tyukavina[1], D. Thau[2], S. V. Stehman[3], S. J. G...**
+ See all authors and affiliations

*Science* 15 Nov 2013:
Vol. 342, Issue 6160, pp. 850-853
DOI: 10.1126/science.1244693



Global Forest Change

Published by Hansen, Potapov, Moore, Hancher et al.

Results from time-series analysis of Landsat images characterizing forest extent and change.

Trees are defined as vegetation taller than 5m in height and are expressed as a percentage per output grid cell as '2000 Percent Tree Cover'. 'Forest Cover Loss' is defined as a stand-replacement disturbance, or a change from a forest to non-forest state, during the period 2000–2018. 'Forest Cover Gain' is defined as the inverse of loss, or a non-forest to forest change entirely within the period 2000–2012. 'Forest Loss Year' is a disaggregation of total 'Forest Loss' to annual time scales.

Reference 2000 and 2018 imagery are median observations from a set of quality assessment-passed growing season observations.

Download the data.

Reset to default view

☑ Data Products
Forest Loss Year (2018 Highlight)

2018
2017
⋮
2000
No loss
Water or no data

☐ Other Data Layers
Primary Humid Tropical Forests

☐ Background Imagery
Year 2000 Bands 5/4/3

Example Locations
Forestry and Tornado in Alabama

Zoom to area

The trail of destruction from the April 27 2011

Published by Hansen, Potapov, Moore, Hancher et al. · Powered by Google Earth Engine · Help

# Such «GLOBAL» approaches have to be used carefully

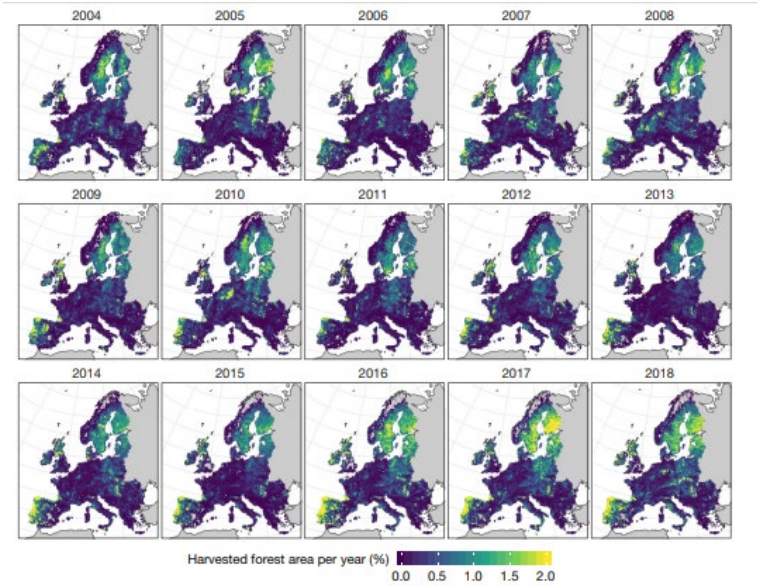
**Article**

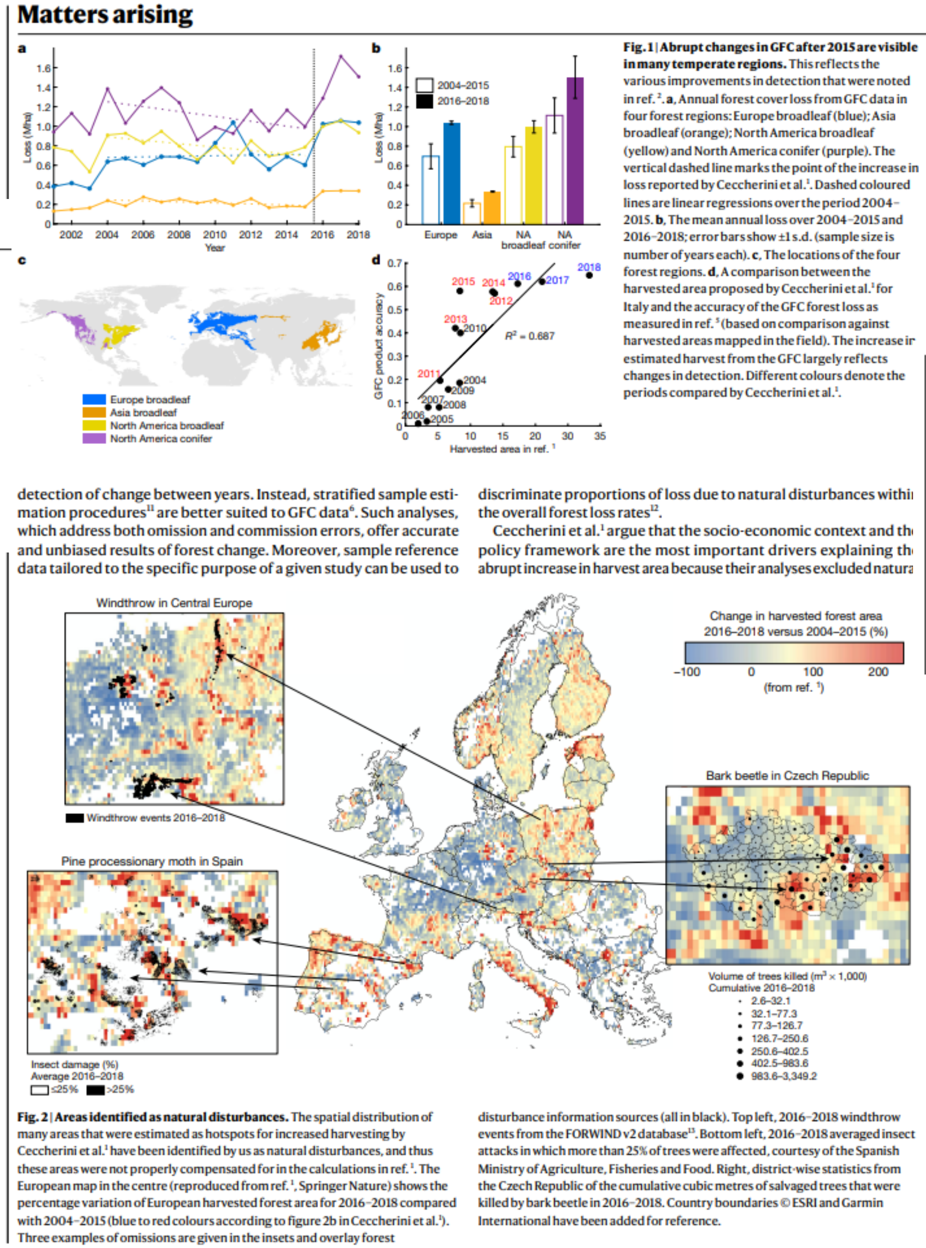
## Abrupt increase in harvested forest area over Europe after 2015

https://doi.org/10.1038/s41586-020-2438-y
Received: 17 May 2019
Accepted: 23 April 2020
Published online: 1 July 2020
Check for updates

Guido Ceccherini[1]✉, Gregory Duveiller[1], Giacomo Grassi[1], Guido Lemoine[2], Valerio Avitabile[1], Roberto Pilli[1] & Alessandro Cescatti[1]

Forests provide a series of ecosystem services that are crucial to our society. In the European Union (EU), forests account for approximately 38% of the total land surface[1]. These forests are important carbon sinks, and their conservation efforts are vital for





**Matters arising**

**Fig. 1 | Abrupt changes in GFC after 2015 are visible in many temperate regions.** This reflects the various improvements in detection that were noted in ref. [2]. **a**, Annual forest cover loss from GFC data in four forest regions: Europe broadleaf (blue); Asia broadleaf (orange); North America broadleaf (yellow) and North America conifer (purple). The vertical dashed line marks the point of the increase in loss reported by Ceccherini et al.[1]. Dashed coloured lines are linear regressions over the period 2004–2015. **b**, The mean annual loss over 2004–2015 and 2016–2018; error bars show ±1 s.d. (sample size is number of years each). **c**, The locations of the four forest regions. **d**, A comparison between the harvested area proposed by Ceccherini et al.[1] for Italy and the accuracy of the GFC forest loss as measured in ref. [5] (based on comparison against harvested areas mapped in the field). The increase in estimated harvest from the GFC largely reflects changes in detection. Different colours denote the periods compared by Ceccherini et al.[1].

detection of change between years. Instead, stratified sample estimation procedures[11] are better suited to GFC data[6]. Such analyses, which address both omission and commission errors, offer accurate and unbiased results of forest change. Moreover, sample reference data tailored to the specific purpose of a given study can be used to discriminate proportions of loss due to natural disturbances withi the overall forest loss rates[12].

Ceccherini et al.[1] argue that the socio-economic context and th policy framework are the most important drivers explaining th abrupt increase in harvest area because their analyses excluded natura

**Fig. 2 | Areas identified as natural disturbances.** The spatial distribution of many areas that were estimated as hotspots for increased harvesting by Ceccherini et al.[1] have been identified by us as natural disturbances, and thus these areas were not properly compensated for in the calculations in ref. [1]. The European map in the centre (reproduced from ref. [1], Springer Nature) shows the percentage variation of European harvested forest area for 2016–2018 compared with 2004–2015 (blue to red colours according to figure 2b in Ceccherini et al.[1]). Three examples of omissions are given in the insets and overlay forest disturbance information sources (all in black). Top left, 2016–2018 windthrow events from the FORWIND v2 database[13]. Bottom left, 2016–2018 averaged insect attacks in which more than 25% of trees were affected, courtesy of the Spanish Ministry of Agriculture, Fisheries and Food. Right, district-wise statistics from the Czech Republic of the cumulative cubic metres of salvaged trees that were killed by bark beetle in 2016–2018. Country boundaries © ESRI and Garmin International have been added for reference.

**Matters arising**

## Concerns about reported harvests in European forests

https://doi.org/10.1038/s41586-021-03292-x
Received: 3 July 2020
Accepted: 26 January 2021
Published online: 28 April 2021
Check for updates

Marc Palahí[1,26]✉, Rubén Valbuena[2,26]✉, Cornelius Senf[3], Nezha Acil[4,5], Thomas A. M. Pugh[4,5,6], Jonathan Sadler[4,5], Rupert Seidl[3], Peter Potapov[7], Barry Gardiner[8], Lauri Hetemäki[1], Gherardo Chirici[9], Saverio Francini[9,10], Tomáš Hlásny[11], Bas Jan Willem Lerink[12], Håkan Olsson[13], José Ramón González Olabarria[14], Davide Ascoli[15], Antti Asikainen[16], Jürgen Bauhus[17], Göran Berndes[18], Janis Donis[19], Jonas Fridman[13], Marc Hanewinkel[17], Hervé Jactel[20], Marcus Lindner[21], Marco Marchetti[22], Róbert Marušák[11], Douglas Sheil[23], Margarida Tomé[24], Antoni Trasobares[25], Pieter Johannes Verkerk[1], Minna Korhonen[1] & Gert-Jan Nabuurs[12,23]

ARISING FROM G. Ceccherini et al. *Nature* https://doi.org/10.1038/s41586-020-2438-y (2020)

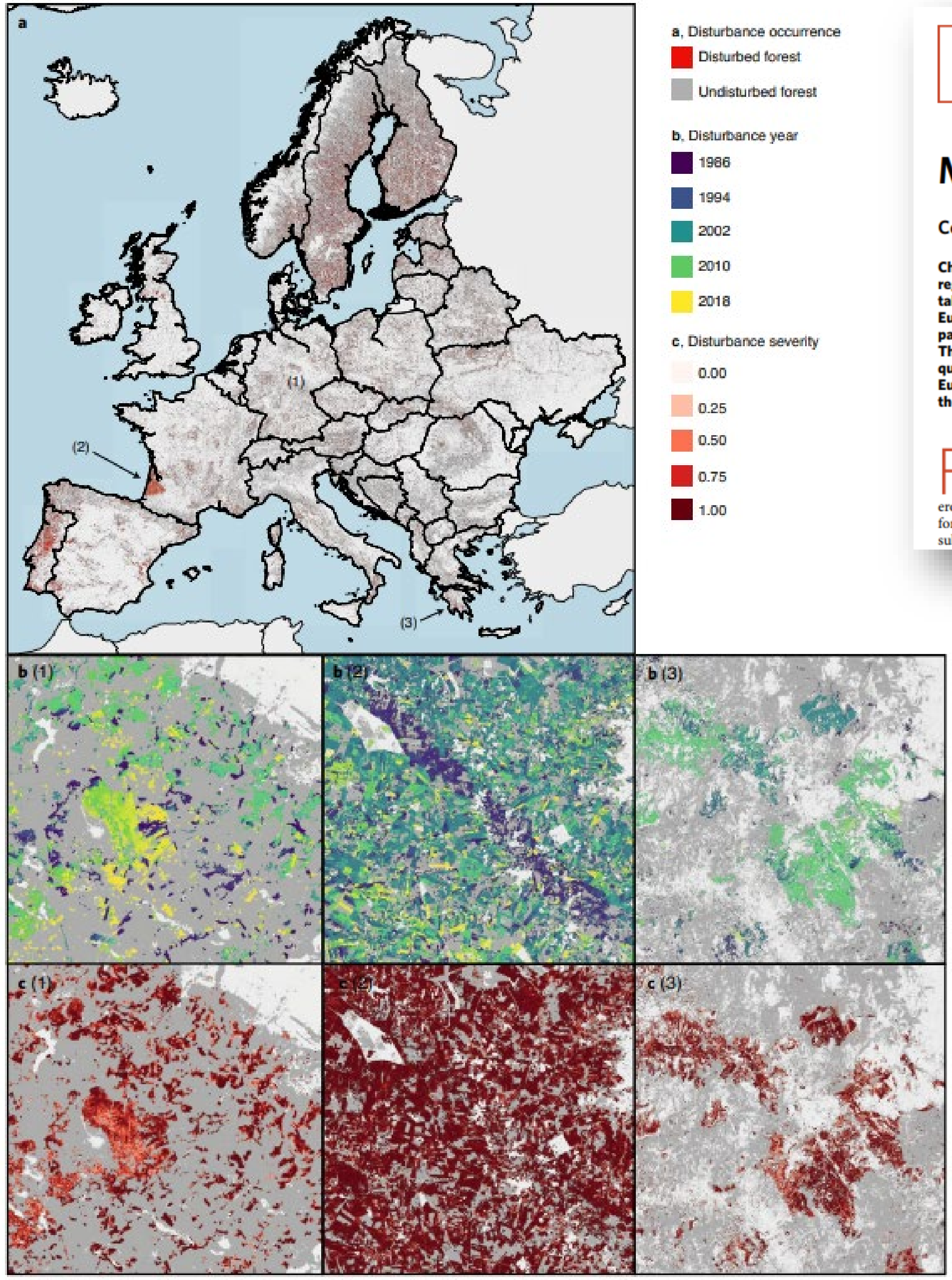
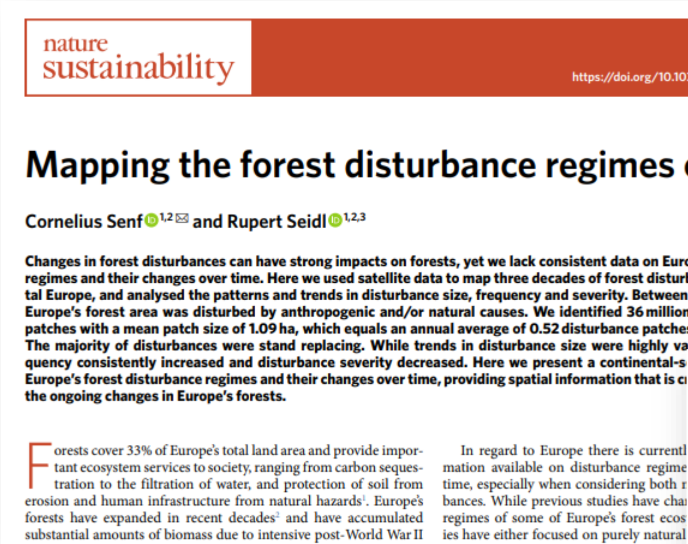


**Fig. 1 | Forest disturbances in Europe, 1986–2016. a**, The occurrence of disturbances across Europe. **b**, Year of disturbance. **c**, Severity of disturbance for three selected areas (scale, 0–1): (1) a bark beetle outbreak of varying severity in and around the Harz National Park (Germany); (2) salvage-logged wind disturbance in an intensively managed plantation forest in the Landes of Gascony (France), with very high disturbance severity; and (3) fire disturbances on the Peloponnese peninsula (Greece), with variable burn severity. Disturbance maps were derived from analysis of >30,000 Landsat images across continental Europe. See Extended Data Fig. 7 for a high-quality version of the main disturbance map.


nature sustainability

ANALYSIS
https://doi.org/10.1038/s41893-020-00609-y

Check for updates

# Mapping the forest disturbance regimes of Europe

Cornelius Senf[1,2] ✉ and Rupert Seidl[1,2,3]

**Changes in forest disturbances can have strong impacts on forests, yet we lack consistent data on Europe's forest disturbance regimes and their changes over time. Here we used satellite data to map three decades of forest disturbances across continental Europe, and analysed the patterns and trends in disturbance size, frequency and severity. Between 1986 and 2016, 17% of Europe's forest area was disturbed by anthropogenic and/or natural causes. We identified 36 million individual disturbance patches with a mean patch size of 1.09 ha, which equals an annual average of 0.52 disturbance patches per km² of forest area. The majority of disturbances were stand replacing. While trends in disturbance size were highly variable, disturbance frequency consistently increased and disturbance severity decreased. Here we present a continental-s**
**Europe's forest disturbance regimes and their changes over time, providing spatial information that is c**
**the ongoing changes in Europe's forests.**

Forests cover 33% of Europe's total land area and provide important ecosystem services to society, ranging from carbon sequestration to the filtration of water, and protection of soil from erosion and human infrastructure from natural hazards[1]. Europe's forests have expanded in recent decades[2] and have accumulated substantial amounts of biomass due to intensive post-World War II

In regard to Europe there is currentl
mation available on disturbance regime
time, especially when considering both r
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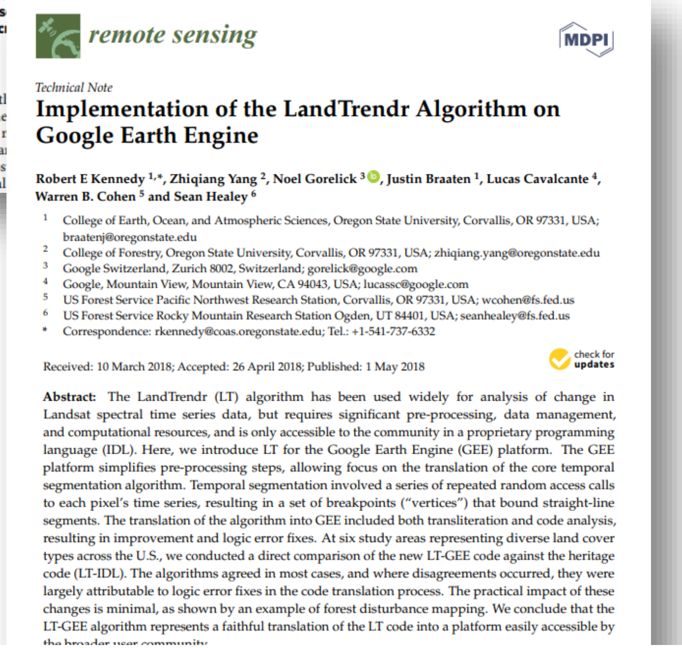
regimes of some of Europe's forest ecos
ies have either focused on purely natural


remote sensing

MDPI

*Technical Note*

# Implementation of the LandTrendr Algorithm on Google Earth Engine

**Robert E Kennedy [1,*], Zhiqiang Yang [2], Noel Gorelick [3], Justin Braaten [1], Lucas Cavalcante [4], Warren B. Cohen [5] and Sean Healey [6]**

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[2] College of Forestry, Oregon State University, Corvallis, OR 97331, USA; zhiqiang.yang@oregonstate.edu
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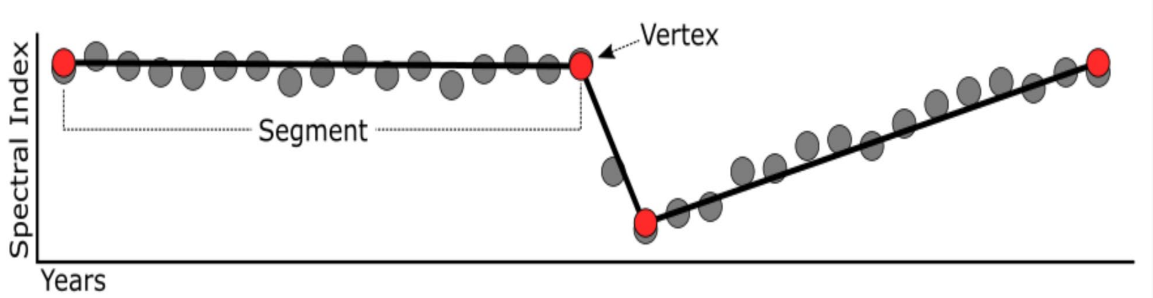
[5] US Forest Service Pacific Northwest Research Station, Corvallis, OR 97331, USA; wcohen@fs.fed.us
[6] US Forest Service Rocky Mountain Research Station Ogden, UT 84401, USA; seanhealey@fs.fed.us
[*] Correspondence: rkennedy@coas.oregonstate.edu; Tel.: +1-541-737-6332

Received: 10 March 2018; Accepted: 26 April 2018; Published: 1 May 2018

check for updates

**Abstract:** The LandTrendr (LT) algorithm has been used widely for analysis of change in Landsat spectral time series data, but requires significant pre-processing, data management, and computational resources, and is only accessible to the community in a proprietary programming language (IDL). Here, we introduce LT for the Google Earth Engine (GEE) platform. The GEE platform simplifies pre-processing steps, allowing focus on the translation of the core temporal segmentation algorithm. Temporal segmentation involved a series of repeated random access calls to each pixel's time series, resulting in a set of breakpoints ("vertices") that bound straight-line segments. The translation of the algorithm into GEE included both transliteration and code analysis, resulting in improvement and logic error fixes. At six study areas representing diverse land cover types across the U.S., we conducted a direct comparison of the new LT-GEE code against the heritage code (LT-IDL). The algorithms agreed in most cases, and where disagreements occurred, they were largely attributable to logic error fixes in the code translation process. The practical impact of these changes is minimal, as shown by an example of forest disturbance mapping. We conclude that the LT-GEE algorithm represents a faithful translation of the LT code into a platform easily accessible by

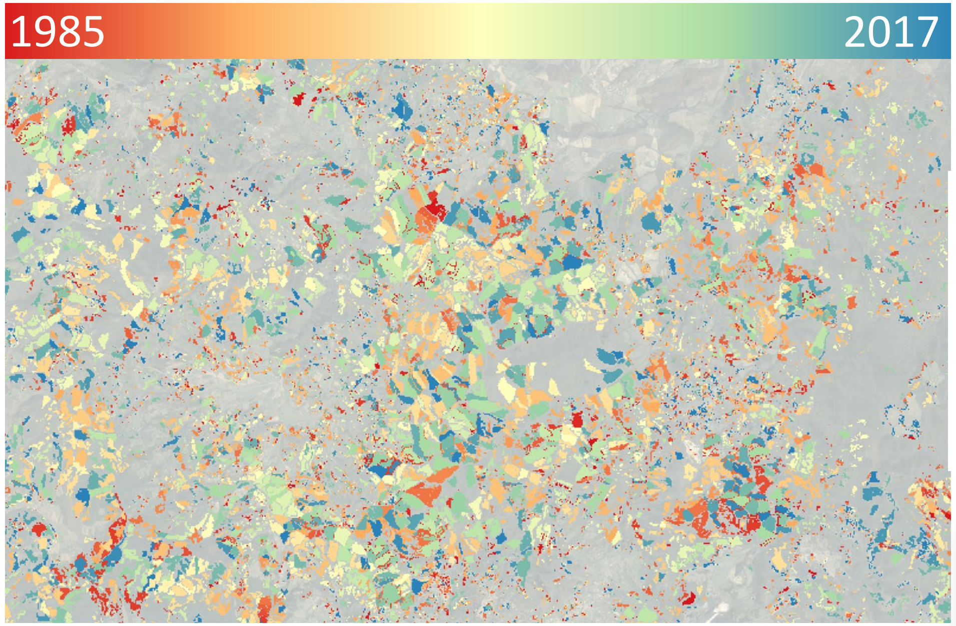
«GLOBAL» approach (LANDTRENDR in GEE) but optimized for EU

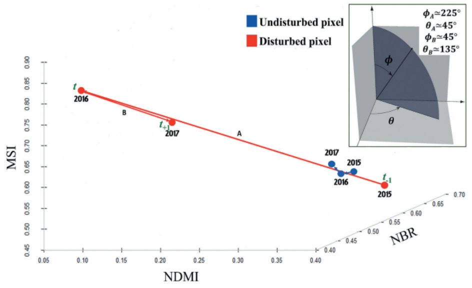


*Remote Sens.* **2018**, *10*, 691; doi:10.3390/rs10050691 www.mdpi.com/journal/remotesensing

# Specific approach for Mediterranean coppices

# 3I3D on Google Earth Engine





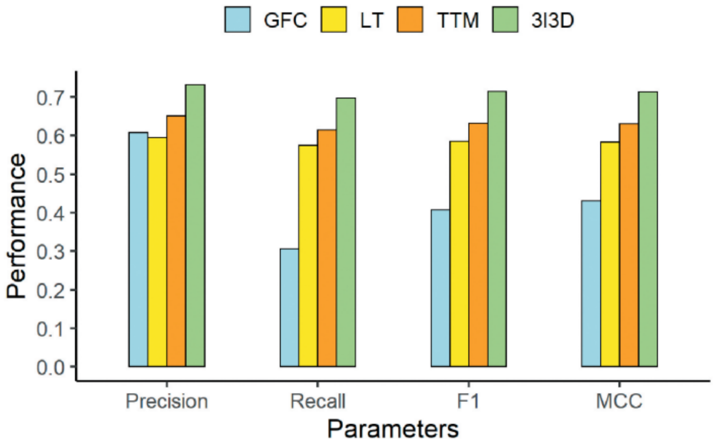
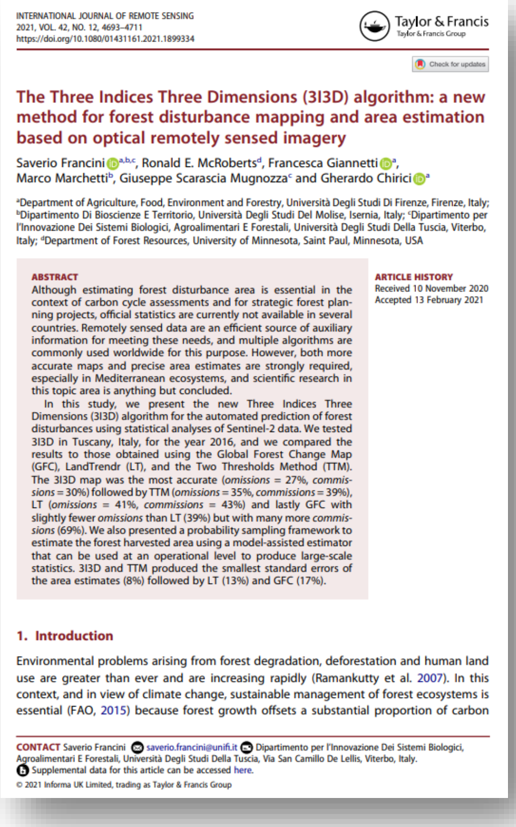


**Figure 3.** 3I3D, TTM, LT and GFC performances comparison. A bar graph comparing the performance of the four algorithms in term of P, R, MCC, and $F_1$.



INTERNATIONAL JOURNAL OF REMOTE SENSING
2021, VOL. 42, NO. 12, 4693–4711
https://doi.org/10.1080/01431161.2021.1899334

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## The Three Indices Three Dimensions (3I3D) algorithm: a new method for forest disturbance mapping and area estimation based on optical remotely sensed imagery

Saverio Francini[a,b,c], Ronald E. McRoberts[d], Francesca Giannetti[a], Marco Marchetti[b], Giuseppe Scarascia Mugnozza[c] and Gherardo Chirici[a]

[a]Department of Agriculture, Food, Environment and Forestry, Università Degli Studi Di Firenze, Firenze, Italy; [b]Dipartimento Di Bioscienze E Territorio, Università Degli Studi Del Molise, Isernia, Italy; [c]Dipartimento per l'Innovazione Dei Sistemi Biologici, Agroalimentari E Forestali, Università Degli Studi Della Tuscia, Viterbo, Italy; [d]Department of Forest Resources, University of Minnesota, Saint Paul, Minnesota, USA

**ABSTRACT**

Although estimating forest disturbance area is essential in the context of carbon cycle assessments and for strategic forest planning projects, official statistics are currently not available in several countries. Remotely sensed data are an efficient source of auxiliary information for meeting these needs, and multiple algorithms are commonly used worldwide for this purpose. However, both more accurate maps and precise area estimates are strongly required, especially in Mediterranean ecosystems, and scientific research in this topic area is anything but concluded.

In this study, we present the new Three Indices Three Dimensions (3I3D) algorithm for the automated prediction of forest disturbances using statistical analyses of Sentinel-2 data. We tested 3I3D in Tuscany, Italy, for the year 2016, and we compared the results to those obtained using the Global Forest Change Map (GFC), LandTrendr (LT), and the Two Thresholds Method (TTM). The 3I3D map was the most accurate (*omissions* = 27%, *commissions* = 30%) followed by TTM (*omissions* = 35%, *commissions* = 39%), LT (*omissions* = 41%, *commissions* = 43%) and lastly GFC with slightly fewer *omissions* than LT (39%) but with many more *commissions* (69%). We also presented a probability sampling framework to estimate the forest harvested area using a model-assisted estimator that can be used at an operational level to produce large-scale statistics. 3I3D and TTM produced the smallest standard errors of the area estimates (8%) followed by LT (13%) and GFC (17%).

**ARTICLE HISTORY**
Received 10 November 2020
Accepted 13 February 2021

### 1. Introduction

Environmental problems arising from forest degradation, deforestation and human land use are greater than ever and are increasing rapidly (Ramankutty et al. 2007). In this context, and in view of climate change, sustainable management of forest ecosystems is essential (FAO, 2015) because forest growth offsets a substantial proportion of carbon

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**CONTACT** Saverio Francini saverio.francini@unifi.it Dipartimento per l'Innovazione Dei Sistemi Biologici, Agroalimentari E Forestali, Università Degli Studi Della Tuscia, Via San Camillo De Lellis, Viterbo, Italy.

Supplemental data for this article can be accessed here.

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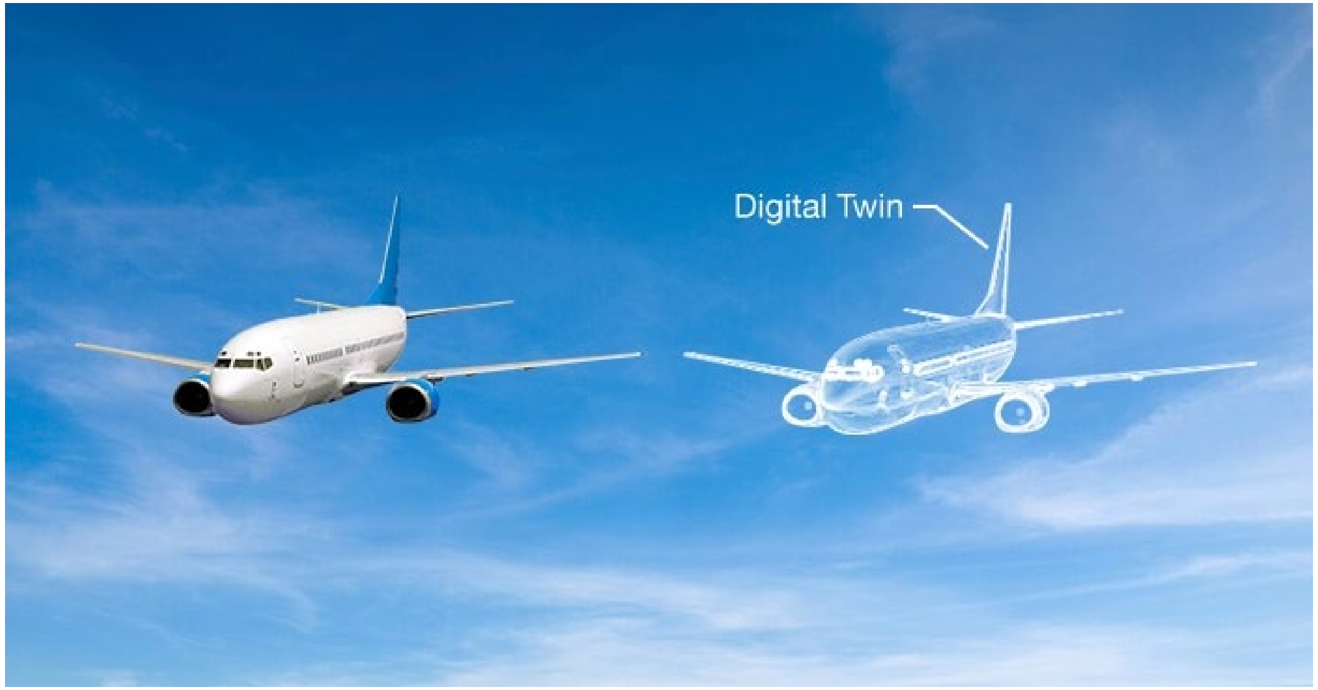
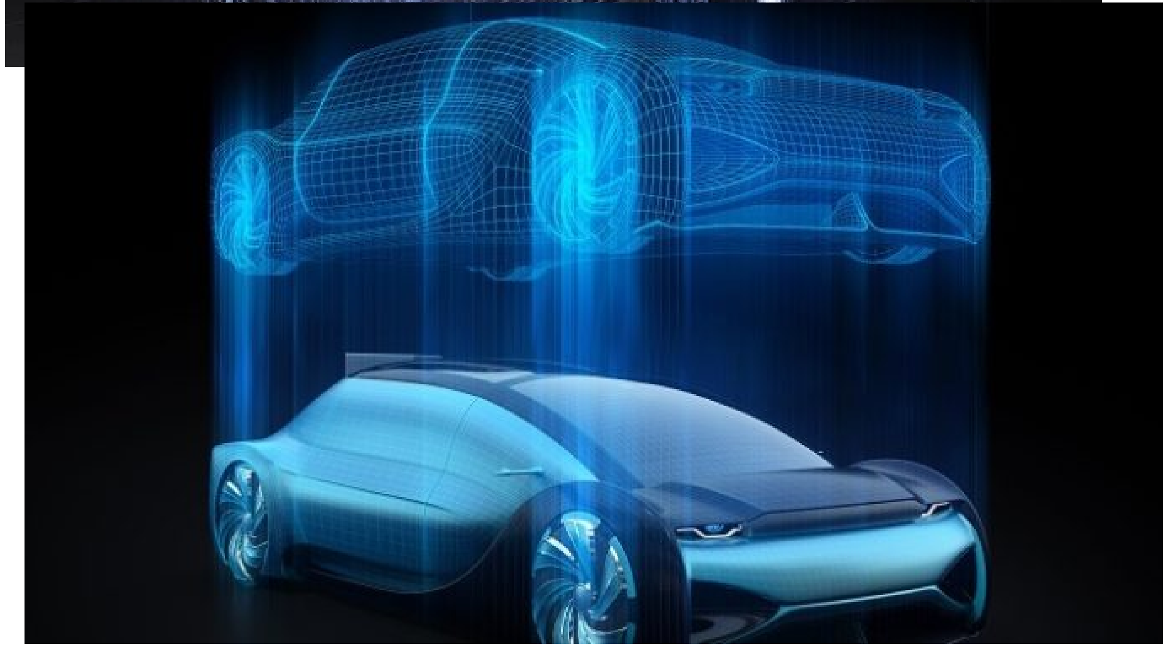
# Digital Twins of **TREES** and **FORESTS**?





A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process (Wiki)

# Digital Twin Earth (DTE)

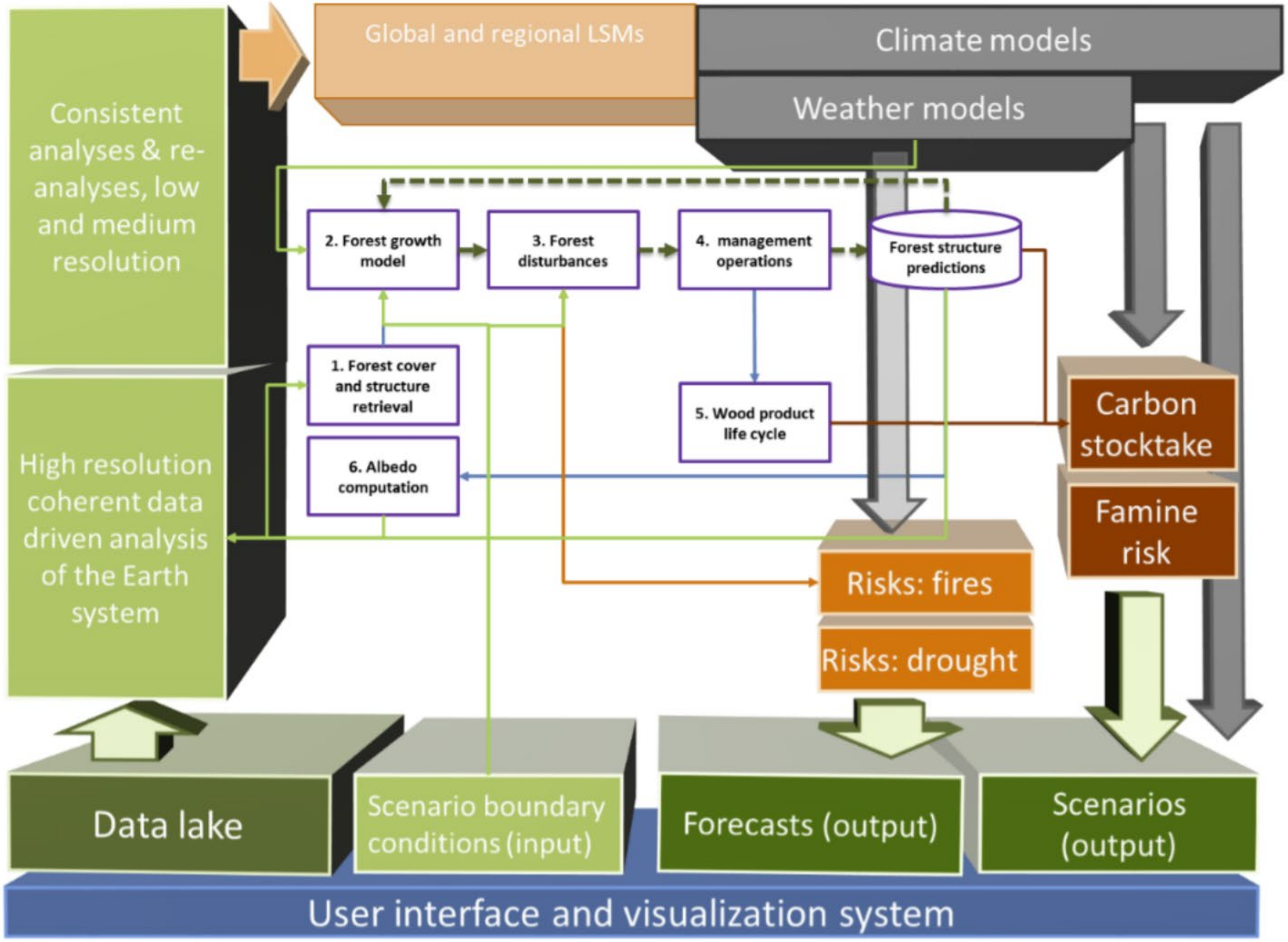
is a high-precision digital model of the Earth that will integrate the Earth system model with modern Earth Observation (EO) data,

## A Methodology for Implementing a Digital Twin of the Earth's Forests to Match the Requirements of Different User Groups

GI_Forum 2021, Issue 1
Page: 130 - 136
Best Practice Paper
Corresponding Author:
matti.mottus@vtt.fi
DOI: 10.1553/giscience2021_01_s130

Matti Mõttus[1], Matthias Dees[2], Heikki Astola[1], Stanisław Dałek[3], Eelis Halme[1], Tuomas Häme[1], Monika Krzyżanowska[3], Annikki Mäkelä[4], Gheorghe Marin[5], Francesco Minunno[4], Gero Pawlowski[2], Juho Penttilä[6] and Jussi Rasinmäki[6]

[1]VTT Technical Research Centre of Finland
[2]Unique GmbH, Freiburg, Germany
[3]Cloudferro Sp z o.o., Warszawa, Poland
[4]University of Helsinki, Finnland
[5]Institutul Național de Cercetare-Dezvoltare în Silvicultură Marin Drăcea (INCDS), Bucharest, Romania
[6]Simosol OY, Riihimäki Finnland



doi:10.1553/giscience2021_01_s130

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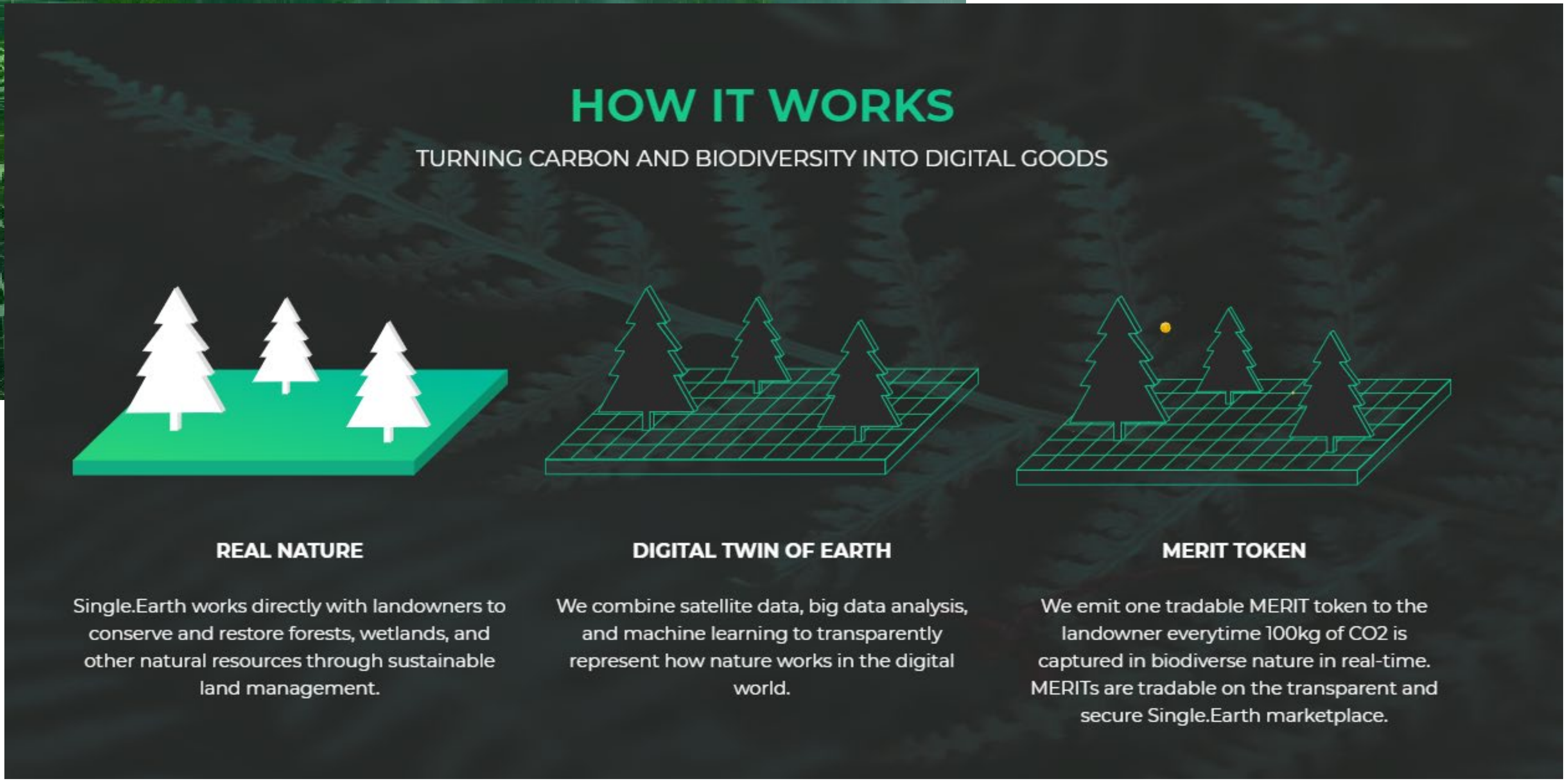

## HOW IT WORKS

TURNING CARBON AND BIODIVERSITY INTO DIGITAL GOODS

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Single.Earth works directly with landowners to conserve and restore forests, wetlands, and other natural resources through sustainable land management.

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**MERIT TOKEN**

We emit one tradable MERIT token to the landowner everytime 100kg of CO2 is captured in biodiverse nature in real-time. MERITs are tradable on the transparent and secure Single.Earth marketplace.

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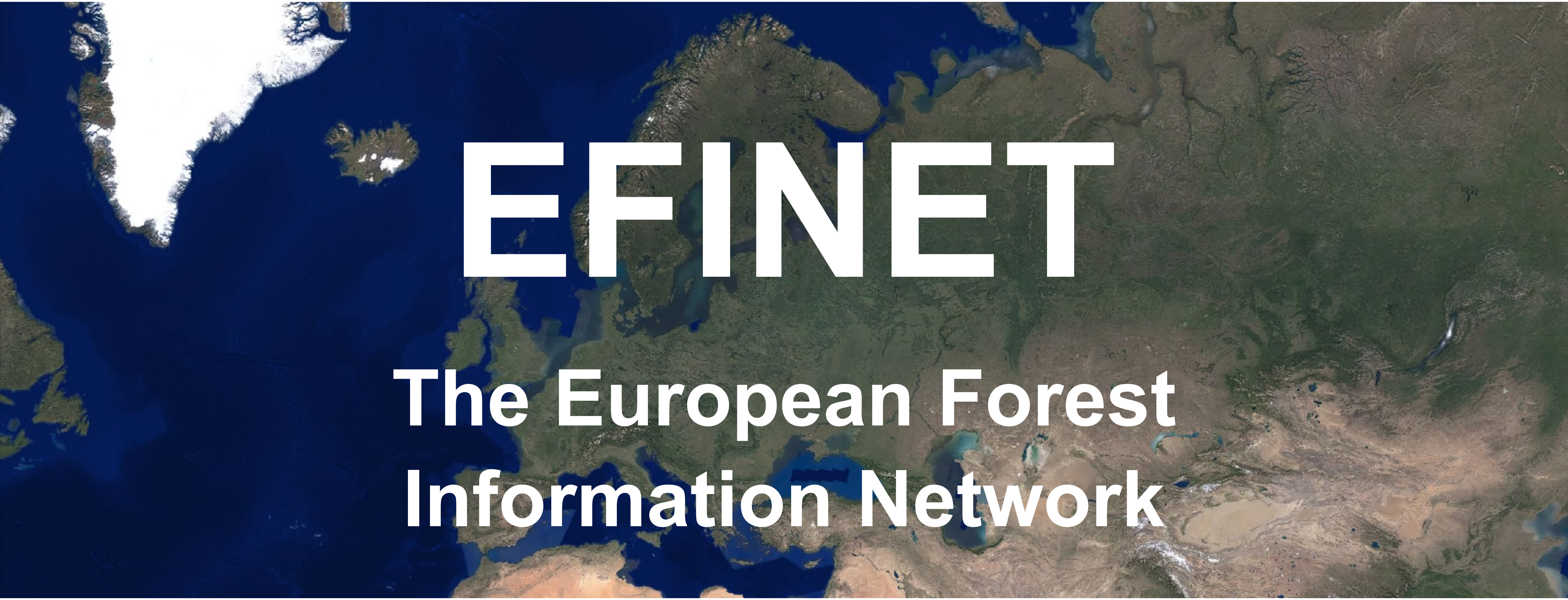
EFI

A proposal for the European Forest Institute (EFI) Network Fund G-01-2021



# EFINET

## The European Forest Information Network

UNIVERSITÀ DEGLI STUDI FIRENZE

PRIFYSGOL BANGOR UNIVERSITY

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LUNDS UNIVERSITET

TECHNISCHE UNIVERSITÄT MÜNCHEN

Norwegian University of Life Sciences

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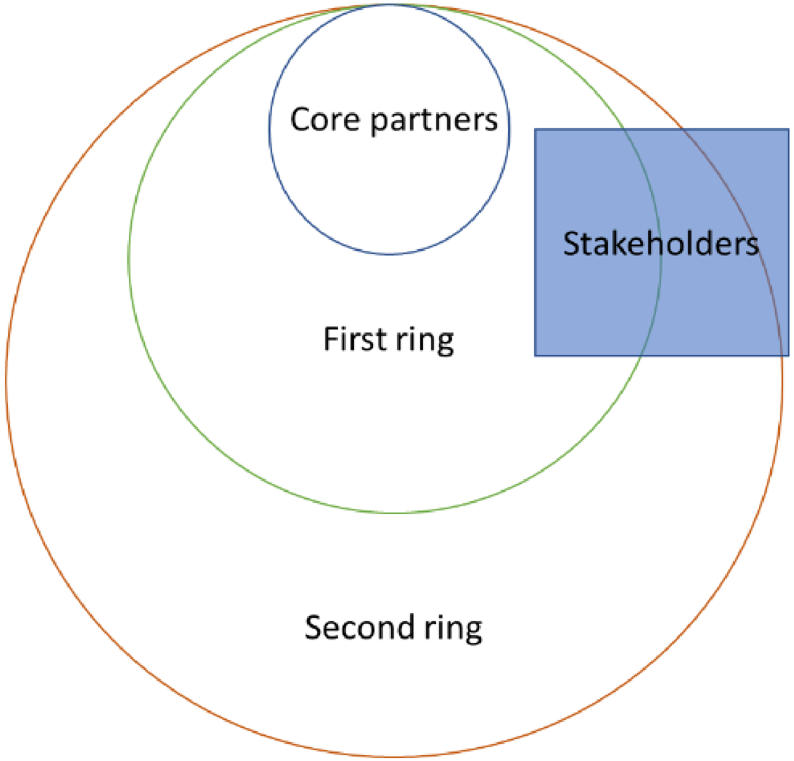
TECHNISCHE UNIVERSITÄT MÜNCHEN

NMBU Norwegian University of Life Sciences

Gherardo Chirici (coordinator)
Rubén Valbuena (deputy coordinator)
Gert-Jan Nabuurs
Cornelius Senf and Rupert Seidl
Thomas Pugh
Erik Næsset and Terje Gobakken



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SLU Swedish University of Agricultural Sciences

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# EFINET
## European Forest Information Network

# AIM

**to develop a conceptual framework and its required institutional network, for derivation of pan-European forest information products and close-to-real-time monitoring of forest changes, forest structural variables, forest biodiversity and forest health at European level**

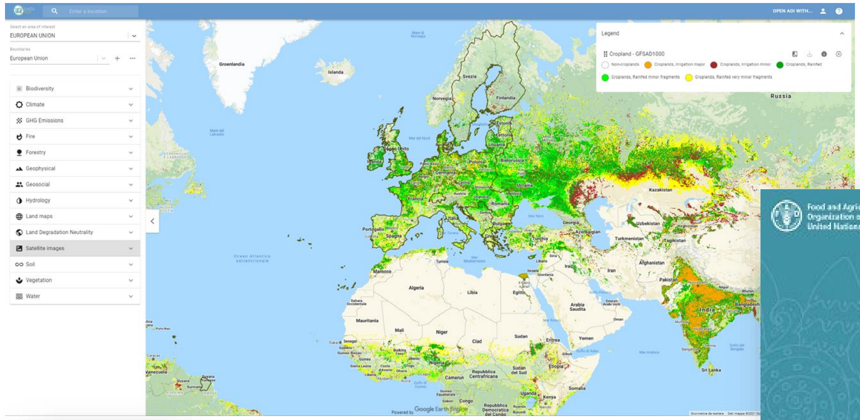
To take the most from both remote sensing data (Landsat/Sentinel and ALS) and field measurements (NFIs)

**WP1** We will first develop the conceptual framework with **stakeholders**, reviews of the literature, identifying the gaps that need to be filled to make pan-European forest information products a reality

**WP2** we will then **test** the proposed forest monitoring system on a selection of relevant case studies representative to the variety of European forests (at least 3), evaluating its strengths and weaknesses in the context of European policy making

**WP3** EFINET will lay the basis for long term changes in monitoring schemes for Europe's forests, including a **strategic plan** for taking the development of a European forest information system forward

**EFINET**
**European Forest Information Network**



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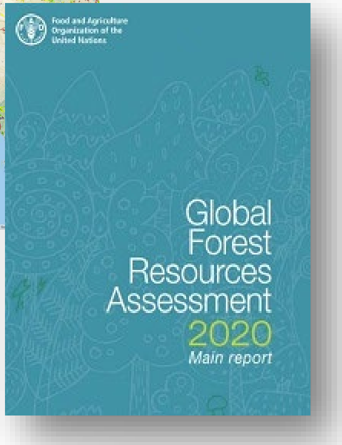

Food and Agriculture Organization of the United Nations

Global Forest Resources Assessment 2020

*Main report*

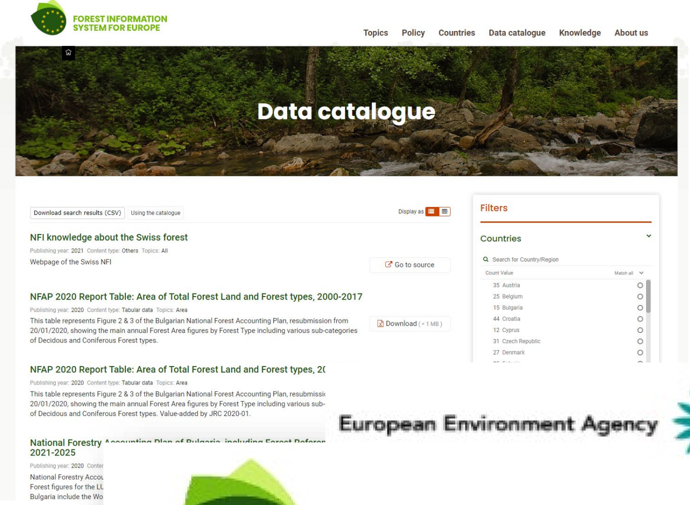
Forest Europe growing life
Ministerial Conference on the Protection of Forests in Europe


***State of Europe's Forests***

*2020*

With the technical support of UNECE
With the technical support of Food and Agriculture Organization of the United Nations

https://foresteurope.org/



**NFI knowledge about the Swiss forest**
Publishing year: 2021 Content type: Others Topics: All
Webpage of the Swiss NFI

**NFAP 2020 Report Table: Area of Total Forest Land and Forest types, 2000-2017**
Publishing year: 2020 Content type: Tabular data Topics: Area
This table represents Figure 2 & 3 of the Bulgarian National Forest Accounting Plan, resubmission from 20/01/2020, showing the main annual Forest Area figures by Forest Type including various sub-categories of Decidous and Coniferous Forest types.

**NFAP 2020 Report Table: Area of Total Forest Land and Forest types, 20**
Publishing year: 2020 Content type: Tabular data Topics: Area
This table represents Figure 2 & 3 of the Bulgarian National Forest Accounting Plan, resubmissi
20/01/2020, showing the main annual Forest Area figures by Forest Type including various sub-
of Decidous and Coniferous Forest types. Value-added by JRC 2020-01.

**National Forestry**
**2021-2025**
Publishing year: 2020 Conte
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Filters

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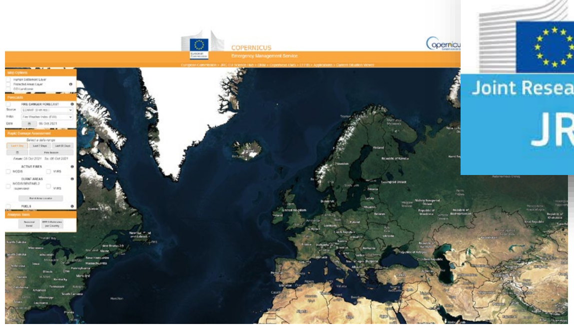
35 Austria ○
25 Belgium ○
15 Bulgaria ○
44 Croatia ○
12 Cyprus ○
31 Czech Republic ○
27 Denmark ○

European Environment Agency

FOREST INFORMATION SYSTEM FOR EUROPE

https://forest.eea.europa.eu/

Copernicus
Europe's eyes on Earth



Joint Research Centre
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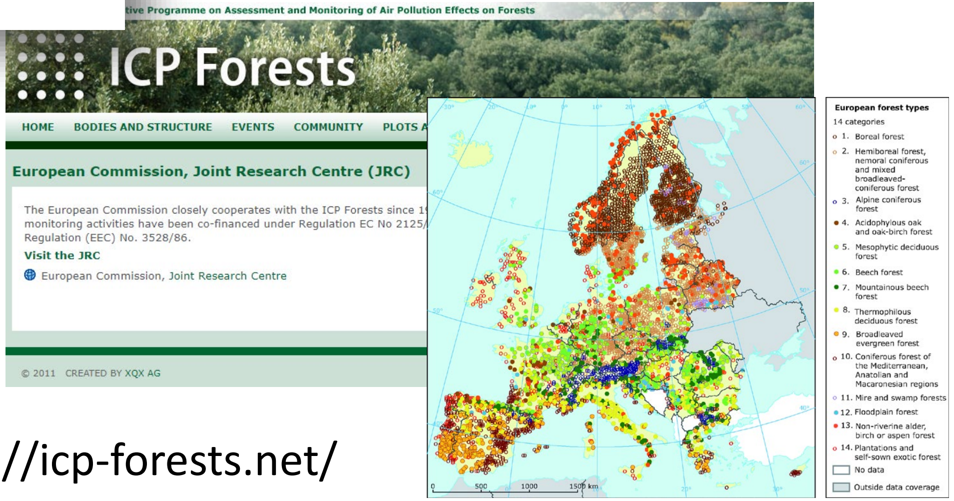
EFFIS, Trees Atlas, EFDAC, …

https://forest.jrc.ec.europa.eu/en/

http://enfin.info/



**European Commission, Joint Research Centre (JRC)**

The European Commission closely cooperates with the ICP Forests since 1
monitoring activities have been co-financed under Regulation EC No 2125/
Regulation (EEC) No. 3528/86.

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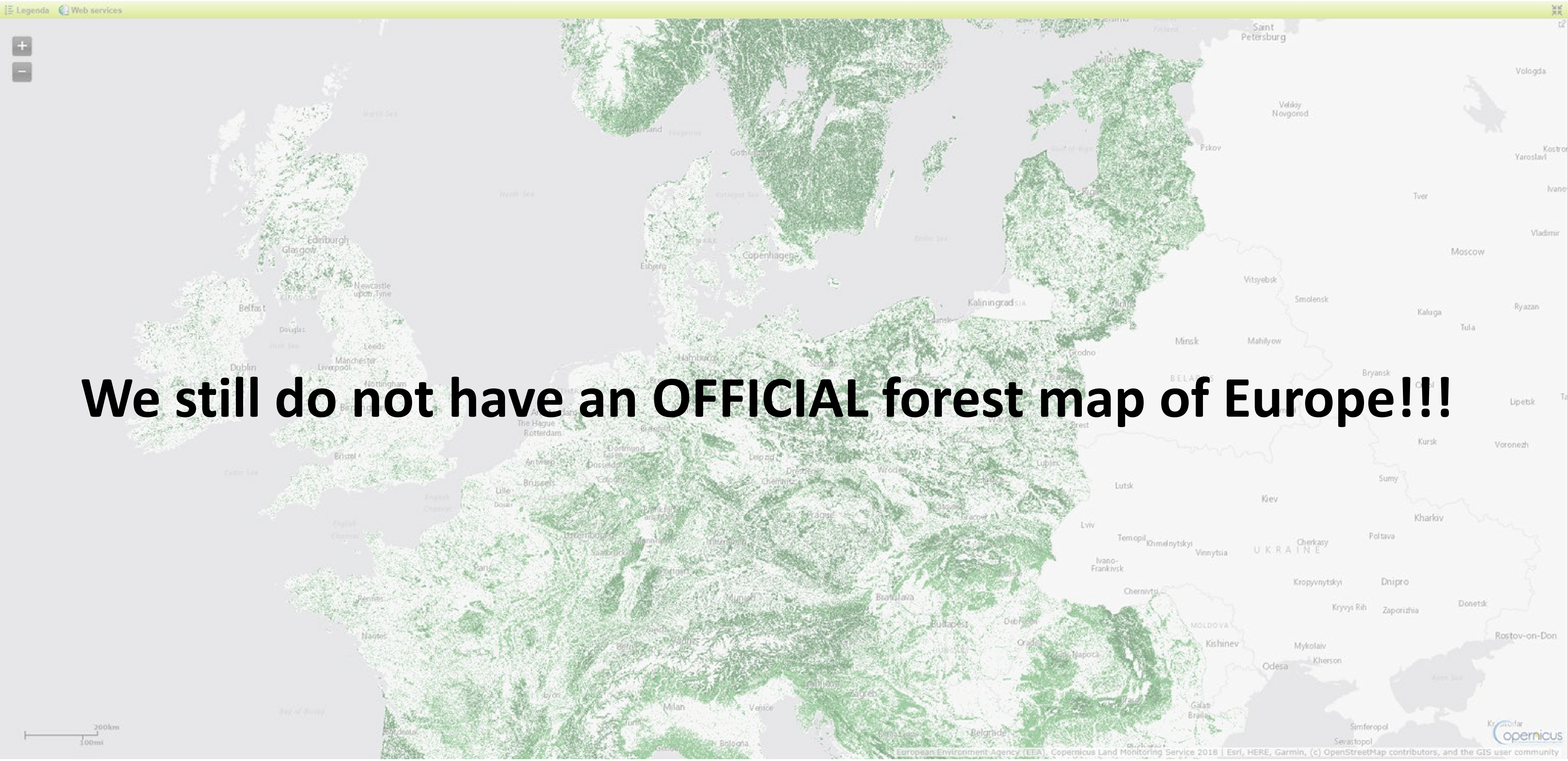
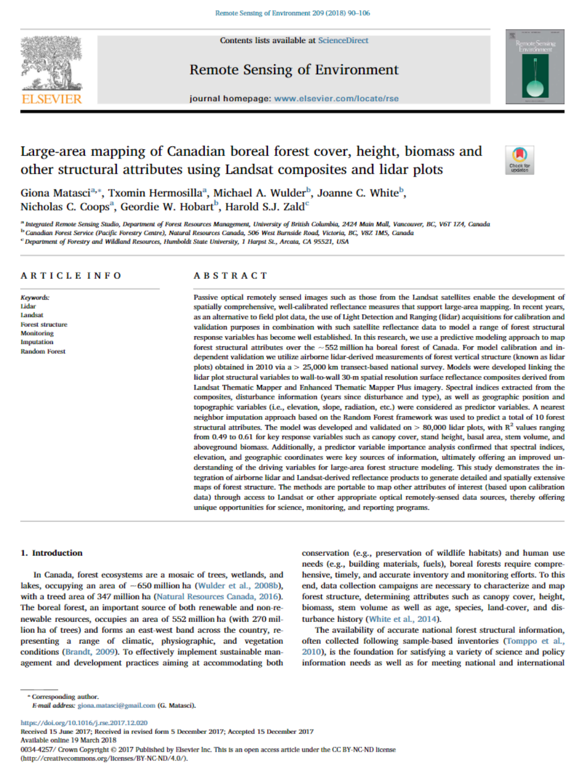


European Environment Agency (EEA), Copernicus Land Monitoring Service 2018 | Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

**We still do not have an OFFICIAL forest map of Europe!!!**

# Take home messagges

- Open access (of a small part of the) NFIs plots (including precise geographic location)
- NFIs are not just data provider
- Multiscale approach with LiDAR plots (see **Canadian example**)
- New technologies (DIGITAL TWINS)…. oh yes there will be always a new technology
- URGENT need for: reference EU LiDAR, EU forest type map, integrated approach
- JOIN EFINET! https://efi.int/efinet



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Large-area mapping of Canadian boreal forest cover, height, biomass and other structural attributes using Landsat composites and lidar plots

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ABSTRACT

Passive optical remotely sensed images such as those from the Landsat satellites enable the development of spatially comprehensive, well-calibrated reflectance measures that support large-area mapping. In recent years, as an alternative to field plot data, the use of Light Detection and Ranging (lidar) acquisitions for calibration and validation purposes in combination with such satellite reflectance data to model a range of forest structural response variables has become well established. In this research, we use a predictive modeling approach to map forest structural attributes over the ~552 million ha boreal forest of Canada. For model calibration and independent validation we utilize airborne lidar-derived measurements of forest vertical structure (known as lidar plots) obtained in 2010 via a > 25,000 km transect-based national survey. Models were developed linking the lidar plot structural variables to wall-to-wall 30-m spatial resolution surface reflectance composites derived from Landsat Thematic Mapper and Enhanced Thematic Mapper Plus imagery. Spectral indices extracted from the composites, disturbance information (years since disturbance and type), as well as geographic position and topographic variables (i.e., elevation, slope, radiation, etc.) were considered as predictor variables. A nearest neighbor imputation approach based on the Random Forest framework was used to predict a total of 10 forest structural attributes. The model was developed and validated on > 80,000 lidar plots, with $R^2$ values ranging from 0.49 to 0.61 for key response variables such as canopy cover, stand height, basal area, stem volume, and aboveground biomass. Additionally, a predictor variable importance analysis confirmed that spectral indices, elevation, and geographic coordinates were key sources of information, ultimately offering an improved understanding of the driving variables for large-area forest structure modeling. This study demonstrates the integration of airborne lidar and Landsat-derived reflectance products to generate detailed and spatially extensive maps of forest structure. The methods are portable to map other attributes of interest (based upon calibration data) through access to Landsat or other appropriate optical remotely-sensed data sources, thereby offering unique opportunities for science, monitoring, and reporting programs.

**1. Introduction**

In Canada, forest ecosystems are a mosaic of trees, wetlands, and lakes, occupying an area of ~650 million ha (Wulder et al., 2008b), with a treed area of 347 million ha (Natural Resources Canada, 2016). The boreal forest, an important source of both renewable and non-renewable resources, occupies an area of 552 million ha (with 270 million ha of trees) and forms an east-west band across the country, representing a range of climatic, physiographic, and vegetation conditions (Brandt, 2009). To effectively implement sustainable management and development practices aiming at accommodating both conservation (e.g., preservation of wildlife habitats) and human use needs (e.g., building materials, fuels), boreal forests require comprehensive, timely, and accurate inventory and monitoring efforts. To this end, data collection campaigns are necessary to characterize and map forest structure, determining attributes such as canopy cover, height, biomass, stem volume as well as age, species, land-cover, and disturbance history (White et al., 2014).

The availability of accurate national forest structural information, often collected following sample-based inventories (Tomppo et al., 2010), is the foundation for satisfying a variety of science and policy information needs as well as for meeting national and international

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Comparable dimensions!