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# Deliverable

# D2.4 Demonstration of the mapping and estimation platform

PathFinder Project

Version: 1.0

30 November 2025

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# I. DOCUMENT CONTROL

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| **Project** | PathFinder (101056907) |
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DISSEMINATION LEVEL [Indicate the dissemination level by underlining the applicable one]

| | |
|---|---|
| **PU** | Public, fully open access |
| **RE** | Restricted to a group specified by the PathFinder Consortium (including the Commission Services) |
| **CO** | Confidential, only for members of the PathFinder Consortium (including the Commission Services) |

# II. DOCUMENT HISTORY

| Version | Date | Author | Change |
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| 0.1 | 19.10.2025 | See above | Full draft for internal review |
| 1.0 | 25.11.2025 | See above | Reviewer comments integrated |

# III. EXECUTIVE SUMMARY

The PathFinder project aims to develop and demonstrate an integrated forest monitoring and pathway assessment system that allows meeting the reporting commitments to European and global policies related e.g. to greenhouse gas and forest biodiversity. One of the main targets of the project is the development of a consistent European Forest Monitoring System (EFMS).

The objective of Work Package 2 (WP2) is to develop and demonstrate a platform to produce high-resolution maps and precise estimates for efficient monitoring of forest attributes including carbon stocks and biodiversity. The document at hand describes the outcome of the platform demonstration and supplements the earlier deliverable 'D2.1 Initial characteristics for mapping and estimation platform' regarding the most recent developments in the approaches used in the demonstration.

The purpose of deliverable D2.4 is to showcase the functionality of a platform concept and demonstrate the feasibility of practical implementation of the platform. The demonstration was conducted building on existing components, namely Forestry TEP (https://f-tep.com/) and nFIESTA (https://gitlab.com/nfiesta), which have been described in deliverable D2.1. In addition, a data visualization and delivery portal was set up.

The PathFinder platform consists of three main modules (Figure 2):

1. Data preparation module
2. Mapping and estimation module
3. Dissemination module

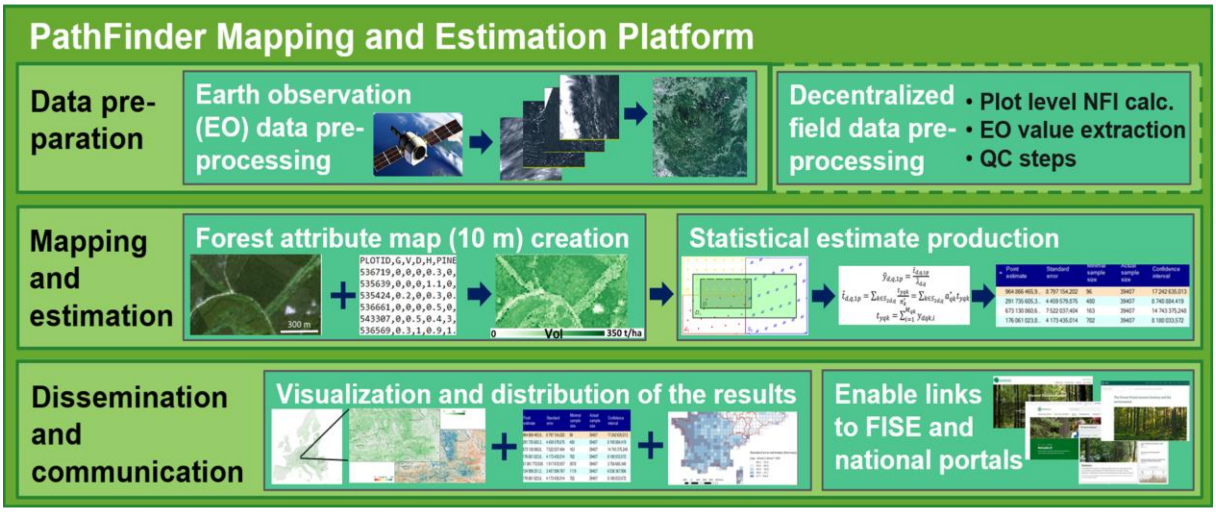


*Figure 1. High-level description of the PathFinder mapping and estimation platform. Note that the field data pre-processing is conducted by national counterparts to maintain data privacy and specific NFI-related background knowledge.*

The demonstration of the 'Data preparation' module was conducted along the lines described in deliverable D2.1, with no major deviations. The outputs from the 'Data preparation' module were used as inputs in the 'Mapping and estimation' module demonstration, which consisted of 1) production of European wide maps for 18 forest attributes in 10 m spatial resolution and 2) production of estimates for 18 target parameters (totals and per hectare values, plus various categorisation, e.g. by species, diameter at breast height or European forest type).

The production of the European wide maps followed the process described in deliverable D2.1 and Miettinen & Breidenbach et al. (2025), with two major exceptions. Firstly, on the contrary to the pilot mapping, the Copernicus tree cover density and forest type products were not used in the final demonstration. Instead, environmental variables (namely elevation and climate data) were used in the final demonstration. Secondly, a fully automated feature bank creation was introduced, aiming to demonstrate the feasibility for operational map production. In the new approach, the 1500 geographically closest plots to the tile centre were extracted from the European wide feature bank for each of the 740 Sentinel-2 tiles used in the processing.

The calculation of the estimates principally followed the description in deliverable D2.1. As part of PathFinder a Graphic User Interface (GUI) for the model-assisted estimation combining field data and maps was implemented in nFIESTA, see Use case for configuration of GREG map totals and ratios · Wiki · nFIESTA / nfiesta gui · GitLab. This functionality was not available at the time of D2.1 compilation. The methodological bases remained unchanged.

Error metrics for the maps were calculated for each of the Sentinel-2 tiles separately. This provided highly localized uncertainty information for the maps. The RMSE% ranged from the around 50 to 90%. Although in the great majority of areas the values were in the range of 50-70%, there were some pockets of over 90% RMSE. Similarly, bias varied from -6% to +5%, although on average the bias was close to zero. The RMSE values for the forest attributes (apart from tree species groups proportions) were on similar levels as reported in earlier studies with k-NN and 10-30 m resolution optical satellite data (Chirici et al. 2016). Bias was generally very small for all the forest attributes (apart from the species proportion layers). This is one of the strengths of the k-NN mapping approach.

It is not possible to make any general assertion concerning the estimators' errors because these depend on sample size, correlation between the map values and field data and last but not least the particular attribute being estimated. However, a general observation is that the model assisted estimators can reduce the standard errors of total estimators (such as total forest area or total above ground biomass) by tens of percents if compared to using field data only. For this reduction it is basically enough to use a forest/non-forest map. If maps contain valuable information also about the forest itself (such as Copernicus Treee Cover Density) the reduction of standard errors occurs also in the mean per hectare estimates (e.g. of biomass). In this case the improvement tends to be notably smaller, unless there is a very high correlation of the auxiliary and the forest attribute also when assessed within the forest mask. The reductions of standard errors are largest for countries using uniform sampling designs, i.e, if plots are distributed evenly across the country territory. In countries which allocate more plots to areas with more forest resource (e.g. Italy with three-phase sampling approach), the improvements tend to be significantly smaller. The reason is that the auxiliary information was used already at the NFI design stage, so there is not much room left for improvement.

The demonstration of the 'Dissemination' module consisted of setting up a PathFinder portal for data download and visualization. This portal allows easy access to the PathFinder mapping and estimation platform output products (i.e. maps and estimates). The portal can be accessed at: https://portal.pathfinder-heu.eu/.

While reported map uncertainties are large for some attributes and in some regions of Europe, together the maps and estimates are among the best and most consistent spatially explicit forest information currently available, showcasing the potential of the PathFinder mapping and estimation platform. The main goal of the demonstration was to prove the scientific and technical feasibility of the system. The flexible implementation approach leaves room for further development within the platform modules and for the operational implementation of the system.

# IV. Abbreviations

| | |
|---|---|
| CLMS | Copernicus Land Monitoring Service |
| CDSE | Copernicus Data Space Ecosystem |
| CSV | Comma-separate values (file format) |
| DEM | Digital Elevation Model |
| EFMS | European Forest Monitoring System |
| EO | Earth Observation |
| EU | European Union |
| FISE | Forest Information System for Europe |
| FO | Field-only |
| Forestry TEP | Forestry Thematic Exploitation Platform |
| FTY | Forest type (CLMS HRL product) |
| HRL | High Resolution Layers |
| GUI | Graphical user interface |
| INSPIRE | Infrastructure for Spatial Information in Europe |
| k-NN | k Nearest Neighbours |
| LUKE | Natural Resources Institute Finland |
| LULUCF | Land use, land-use change, and forestry |
| MA | Model-Assisted estimator |
| NFI | National Forest Inventory |
| nFIESTA | new Forest Inventory EStimation and Analysis |
| NIBIO | Norwegian Institute of Bioeconomy Research |
| NLI | Národní lesnický Ioannis (Czech Forestry Institute) |
| OGC | Open GeoSpatial Consortium |
| RMSE | Root Mean Squared Error |
| SFTP | SSH File Transfer Protocol |
| TCD | Tree cover density (CLMS HRL product) |
| VTT | Technical Research Centre of Finland Ltd. |

# Contents

# 1. Introduction

The PathFinder project aims to develop and demonstrate an integrated forest monitoring and pathway assessment system that allows reporting to European and global policies related e.g. to greenhouse gas and forest biodiversity. The system includes high-resolution mapping and precise estimation of forest attributes using a combination of field and remotely sensed data. The forest information of the monitoring system feeds into a new scenario framework that forecasts future forest scenarios and outcomes of forest management alternatives, and further on to forest management pathway assessment.

One of the main targets of the project is the development of a European Forest Monitoring System (EFMS) that combines field observations and remote sensing data in consistent national and EU level LULUCF Greenhous Gas Inventories and provides information on biodiversity and other key forest ecosystem services. The EFMS furthermore includes a future forest forecasting and policy pathway assessment system.

The objective of Work Package 2 (WP2) is to develop and demonstrate an approach to produce high-resolution maps and precise estimates for efficient monitoring of forest attributes including carbon stocks and biodiversity. The main outcome of WP2 is the demonstration of a mapping and estimation platform, the design of which was developed in 'Task 2.1: Developing a mapping and estimation platform'. The functionality of the platform is demonstrated in 'Task 2.4: Demonstration of the mapping and estimation platform'. The document at hand lists the different components of the demonstration and supplements the earlier deliverable 'D2.1 Initial characteristics for mapping and estimation platform' regarding the most recent developments in the approaches used in the demonstration. It is important to note, however, that D2.4 is of type 'DEM — Demonstrator, pilot, prototype'. Thus, the document at hand is not the deliverable itself, but merely describes the components that form the deliverable and where to find them.

The purpose of deliverable D2.4 is to showcase the functionality of a platform concept and demonstrate the feasibility of practical implementation of the platform. The demonstration was conducted building on existing components, namely Forestry TEP (https://f-tep.com/) and nFIESTA (https://gitlab.com/nfiesta), which have been described in deliverable D2.1. In addition, a data visualization and delivery portal was set up that allows viewing and downloading for analyses.

This deliverable has been divided into six sections:

1. *Introduction*, which provides the context for the document within the project.
2. *Pathfinder platform modules*, which describes the overall structure of the platform and presents the three modules demonstrated.
3. *Data preparation module demonstration,* which reports the demonstration items and gives necessary background for the data preparation module demonstration.
4. *Mapping and estimation module demonstration,* which reports the demonstration items and gives necessary background for the mapping and estimation module demonstration.
5. *Dissemination module demonstration*, which reports the demonstration item and gives necessary background for the dissemination module demonstration.
6. *Discussion,* which provides justifications for the key choices made during the demonstration, discusses the findings on the outputs and raises some points for future development.

# 2. PathFinder platform modules

The PathFinder platform consists of three main modules (Figure 2):

1. Data preparation module
2. Mapping and estimation module
3. Dissemination and communication module

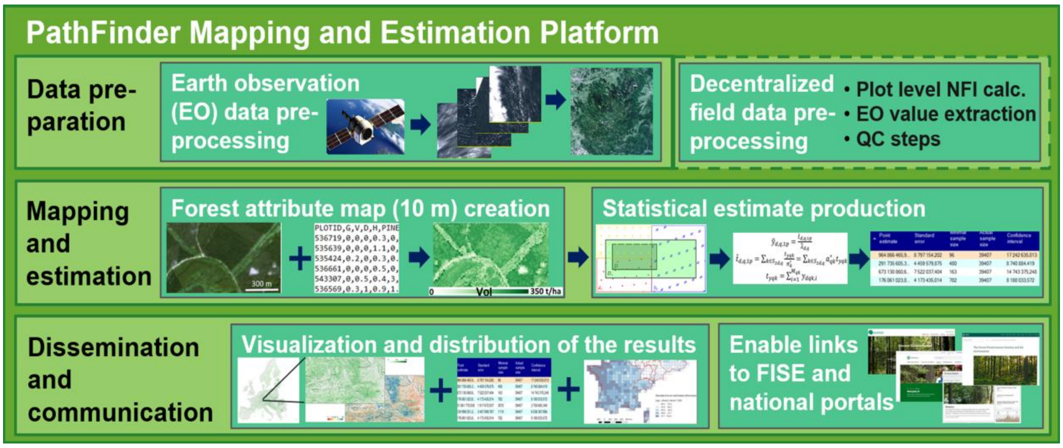


*Figure 2. High-level description of the PathFinder mapping and estimation platform. Note that the field data pre-processing is conducted by national counterparts to maintain data privacy and specific NFI-related background knowledge.*

Each of the three main modules consists of several components that together allow to conduct the tasks required in different phases of the data pre-processing, analysis and distribution. Together these three modules form a comprehensive system that allows annual processing and analysis of the Earth observation (EO), auxiliary and field datasets.

The ***Data preparation*** module enables pre-processing tasks for EO, auxiliary and field datasets. Note that large part of the field data pre-processing is conducted by NFI teams in their own premises (due to privacy reasons and the necessary, specific NFI-related background knowledge). Tools are provided to the NFI teams for the data processing as well as checking the correctness of the outputs. The demonstration items of the *Data preparation* module are listed in Section 3.

The ***Mapping and estimation*** module facilitates synergistic use of EO and field datasets and thereby form the core of the PathFinder platform. This is the module where harmonized forest information from 10 m spatial resolution to European level on annual basis is produced using data from the *Data preparation* module. The demonstration items of the *Mapping and estimation* module are listed in Section 4.

The ***Dissemination*** module enables visualization and distribution of the outputs to the users. Note that this module was called the *Results* module in deliverable D2.1. It was renamed to dissemination module for this deliverable to better convey the main objective of the module, to facilitate dissemination of the outputs of the platform. The demonstration item of the *Dissemination* module is presented in Section 5.

It is important to emphasize that during the project the main aim is to demonstrate the feasibility of the platform concept. This is achieved by building tools and processing components that fulfil the required functionalities of the platform and demonstrate the technical feasibility by running European wide demonstrations. The platform functionality is demonstrated using a set of existing infrastructures. In the future, in a potential operational deployment, the platform can be implemented on and operated in other processing infrastructure if so desired.

# 3. Data preparation module demonstration

## 3.1 Demonstration items

The demonstration of the *Data preparation* module consists of the following items:

1. Processing of NFI field data into nFIESTA and Forestry TEP compatible formats
2. Creation of a European wide Sentinel-2 composite image mosaics
3. Preparation of auxiliary datasets for nFIESTA and Forestry TEP

## 3.2 Preparation of NFI field data

The preparation of NFI data followed the process described in deliverable D2.1. All countries delivered data in the CSV file format as described in deliverable D2.1. Table 1 summarizes the NFI plot data available for the final demonstration of the PathFinder platform. Note that Spain (ES) uses regional periodic design, so there is no panel that is representative for the whole country in any given period. Therefore, its measures referring to last panel are not comparable to the rest of the countries.

*Table 1. Summary of NFI field data provided for the final demonstration of the PathFinder platform.*

| Country | Period of provided data | Number of NFI cycles | Length of last field campaign [year] | Number of forest plots | Period of most recent panel | Number of plots/PSUs* in l most recent panel | Mean sampling weight of PSU in most recent panel [ha] |
|---|---|---|---|---|---|---|---|
| AT | 2016-2023 | 2 | 6 | 13780 | 2023-2023 | 3701/929 | 9030 |
| BE | 2008-2022 | 2 | 15 | 5688 | 2020-2022 | 3366/3366 | 1000 |
| CH | 2016-2022 | 2 | 9 | 4733 | 2022-2022 | 2295/2295 | 1800 |
| CZ | 2011-2020 | 2 | 5 | 21842 | 2020-2020 | 7883/7883 | 1000 |
| DE | 2011-2017 | 2 | 2 | 13825 | 2016-2017 | 22357/5617 | 6350 |
| ES | 1993-2022 | 3 | 16 | 336 930 | 2020-2022 | 11709/11709 | 100 |
| FI | 2019-2022 | 1 | 5 | 36483 | 2022-2022 | 14688/1692 | 19410 |
| FR | 2017-2021 | 1 | 5 | 29568 | 2021-2021 | 38403/38403 | 1430 |
| IE | 2015-2022 | 2 | 3 | 3943 | 2020-2022 | 17423/17423 | 400 |
| IT | 2017-2020 | 1 | 4 | 6993 | 2017-2020 | 10228/10228 | 2950 |
| NO | 2011-2021 | 3 | 5 | 25587 | 2021-2021 | 4390/4390 | 7380 |
| PL | 2011-2022 | 3 | 5 | 77601 | 2022-2022 | 19741/3960 | 7900 |
| SE | 2012-2021 | 2 | 5 | 47783 | 2021-2021 | 10536/1443 | 32910 |
| SI | 2012-2018 | 2 | 1 | 1519 | 2018-2018 | 1268/1268 | 1600 |
| **All** | 1993-2023 | - | - | 626 275 | - | 167 988/110 606 | - |

**PSU - primary sampling unit, either a single plot or cluster of several plots depending on NFI design*

## 3.3 Preparation of EO data

The preparation of EO data followed the process described in deliverable D2.1. Annual growing season cloud free Sentinel-2 composite image mosaics of 2020, 2021, and 2024 were used as the EO dataset in the final demonstration. The processing of all of the three composite image mosaics was conducted on the Forestry TEP platform. The compositing was conducted by Terramonitor[1], using an algorithm described in detail in Miettinen et al. (2021). The processing was done in Sentinel-2 tiles, which is the standard format in which Sentinel-2 data is made available. Composites of the years 2020 and 2021 had already been produced prior to the PathFinder project but were used both in the pilot mapping (Miettinen et al. 2025) as well as in the final demonstration. The 2024 mosaic was created as part of the PathFinder project and was used in the final demonstration.

## 3.4 Preparation of auxiliary datasets

In addition to the EO data described above in section 3.3, two auxiliary datasets were used in the European wide mapping. These include 1) a Copernicus 30 m digital elevation model (DEM) (https://dataspace.copernicus.eu/) and 2) climate data (1981-2010) including mean annual temperature and precipitation (Karger et al. 2017, 2018; downloaded from https://chelsa-climate.org/). The auxiliary datasets were used in their original format. The DEM was accessed directly in the Copernicus Data Space Ecosystem by Forestry TEP processing scripts. The climate data were uploaded to the Forestry TEP for the map production.

As for the preparation of the auxiliary data for estimation, the total areas of categories (broadleaved, coniferous, and non-forest) of the Copernicus 2018 Forest Type map and the total areas covered by trees according to Tree Cover Density map were calculated by nFIESTA GIS data module (Home · Wiki · nFIESTA · GitLab).

## 3.5 Data preparation module output datasets

The output datasets from the *Data preparation* module are listed in Table 2. These include three different types of products, namely EO datasets, auxiliary datasets and nFIESTA input files. Detailed description of the various nFIESTA .csv input files is provided at: https://gitlab.com/nfiesta/pathfinder_demo_study/-/wikis/Description%20of%20CSV%20files

*Table 2. Data preparation module output datasets.*

| Dataset | Type | Features |
|---|---|---|
| Sentinel-2 composite imagery 2020 | EO (.tif) | B02, B03, B04, B05, B08, B11, B12 + quality bands |
| Sentinel-2 composite imagery 2024 | EO (.tif) | B02, B03, B04, B05, B08, B11, B12 + quality bands |
| Copernicus 30 m DEM | Auxiliary (.tif) | Elevation above sea level |
| Chelsa v.2 climate data 1981-2010 | Auxiliary (.tif) | Mean annual temperature |
| Chelsa v.2 climate data 1981-2010 | Auxiliary (.tif) | Mean annual precipitation |
| CLMS HRL Tree Cover Density 2018 | Auxiliary (.tif) | Tree canopy coverage, in % |
| CLMS HRL Forest Type 2018 | Auxiliary (.tif) | Forest type: Broadleaf, Conifer and non-forest |
| Forest Change 2000-2021 (Hansen et al. 2013) | Auxiliary (.tif) | Year of detected tree cover clearance |
| strata_sets.csv | nFIESTA (.csv) | List of strata sets |
| strata.csv | nFIESTA (.csv) | Strata sets |
| cluster_configurations.csv | nFIESTA (.csv) | List of cluster configurations |
| panels.csv | nFIESTA (.csv) | List of panels |

[1] https://www.terramonitor.com/

| | | |
|---|---|---|
| clusters.csv | nFIESTA (.csv) | List of plot clusters |
| plots.csv | nFIESTA (.csv) | List of plots |
| inventory_campaigns.csv | nFIESTA (.csv) | List of inventory campaigns |
| reference_year_sets.csv | nFIESTA (.csv) | List of reference-year sets |
| reference_year_sets_ panels_associations.csv | nFIESTA (.csv) | Possible combinations of panels and reference-year sets |
| plot_measurement_ dates.csv | nFIESTA (.csv) | List of plots with dates of their assessment |
| plot_cell_associations.csv | nFIESTA (.csv) | Spatial linkage of plots to the estimation cells |
| plot_target_data.csv | nFIESTA (.csv) | Plot-values of target variables |
| plot_target_data_ availability.csv | nFIESTA (.csv) | Missing target variables or categories |
| plot_auxiliary_data.csv | nFIESTA (.csv) | Plot-level values of auxiliary variables |

# 4. Mapping and estimation module demonstration

## 4.1 Demonstration items

The demonstration of the *Mapping and estimation* module consists of the following items:

1. European wide maps for 18 forest attributes in 10 m spatial resolution including growing stock volume, above ground biomass (AGB), conifer proportion, quadratic mean diameter, basal area, height, gross annual increment, net annual increment and proportions of 10 species groups (of AGB).
2. Design based estimates for 18 forest related target parameters including forest area, above ground biomass, growing stock and its change, lying deadwood, net and gross annual increment (totals and ratios, i.e., per hectare values)

## 4.2 European wide maps

The production of the European wide maps followed the process described in deliverable D2.1 and in Miettinen & Breidenbach et al. (2025a, 2025b). Notable modification since D2.1 include change in the auxiliary layers and the creation of the feature banks. The Copernicus tree cover density and forest type products were not used in the map production in the final demonstration. Instead, environmental variables (described in Section 3.4) were used. This change was implemented to demonstrate the capability to produce timely maps without dependencies on other EO based products. In addition, the way the reference plots were used was entirely changed. For each of the 740 processed Sentinel-2 tiles, 1500 plots that were geographically closest to the tile centre were extracted from the European wide feature bank.

Error metrics were calculated for each of the tiles separately. Using the 1500 plots that were used in k-NN mapping, the error metrics were calculated using leave-one-out cross-validation. Error metrics were calculated with equations provided in Miettinen & Breidenbach et al. (2025a). It is important to note that for tiles without NFI sample plots, the error metrics were calculated within the tile feature bank containing the closest 1500 NFI sample plots, located fully outside the tile in question. Because the forest structure represented by the closest feature bank is necessarily different than the actual local condition, the error metrics will be more or less biased for these tiles.

Apart from these modifications, the maps were produced as described in deliverable D2.1 'Initial characteristics for mapping and estimation platform' and in Miettinen & Breidenbach et al. (2025a).

Specifications of the mapped variables, used feature banks and map uncertainty information is provided in Miettinen & Breidenbach (2025b).

## 4.3 Design-based estimates

Estimates were calculated by the nFIESTA GUI that is connected to PostgreSQL databases hosted on a rented high-performance server in the Czech Republic. Several databases had to be created depending on the area covered by data of a specific variable. Not all countries provided the same list of variables and consequently the estimation cells (regions of estimation going across country borders) had to be cut at the limits of the covered area. This operation is not doable as a mere database filtering but requires creation of new versions of geometries of estimation cells. Without the adjustment of the estimation cells, the model-assisted estimates would inappropriately assume the totals of auxiliary variables in the full extent of the estimation cell. The estimate would match the original estimation cell, and it would represent a mixture of design-based and model-based inference. This is not convenient in terms of results interpretation. Therefore, we adjust the estimation cells to areas covered by NFI data. It cannot be presumed all countries provide data for all variables, and a solution other than creation of separate databases can be considered in future nFIESTA versions.

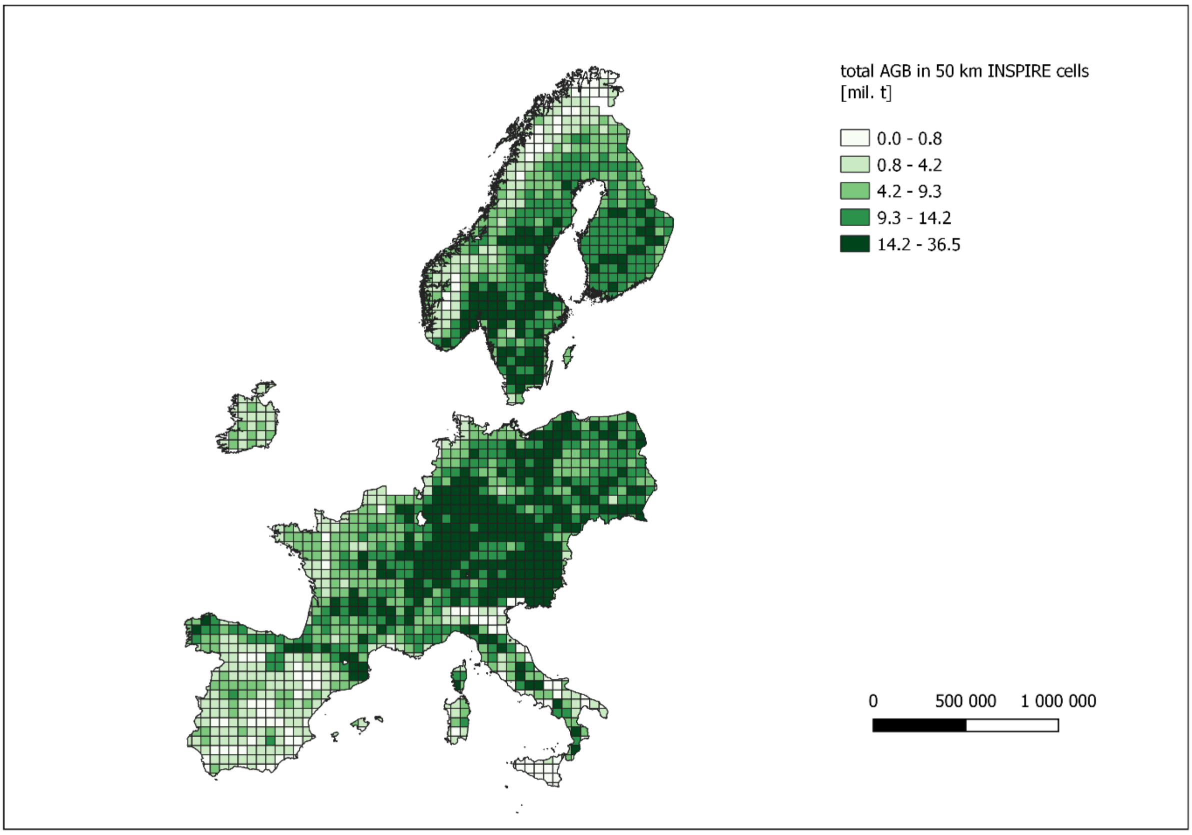


*Figure 3: Model-assisted estimates of total above ground biomass by INSPIRE 50 km cells (14 European countries, year 2020)*

Until the compilation of this report, totals of forest area and above ground biomass (AGB) were estimated. Figure 3 shows model-assisted (MA) estimates of total AGB combining field data and Copernicus Forest Type and Tree Cover Density maps (2018).

Proportion of forest in the estimation cell (Figure 4) and per hectare values of AGB were estimated as well. The estimates were calculated for INSPIRE cells 100 km and 50 km, for biogeographical regions of Europe and for validation purposes also for NUTS0 (Country) level. Estimates were produced for years 2019 till 2022 with again varying area covered by data. In addition to single-phase estimators using field data only, Model-assisted estimates (MA) were also calculated. The auxiliary variables were those of Copernicus 2018, namely Forest Type map and Tree Cover Density map.

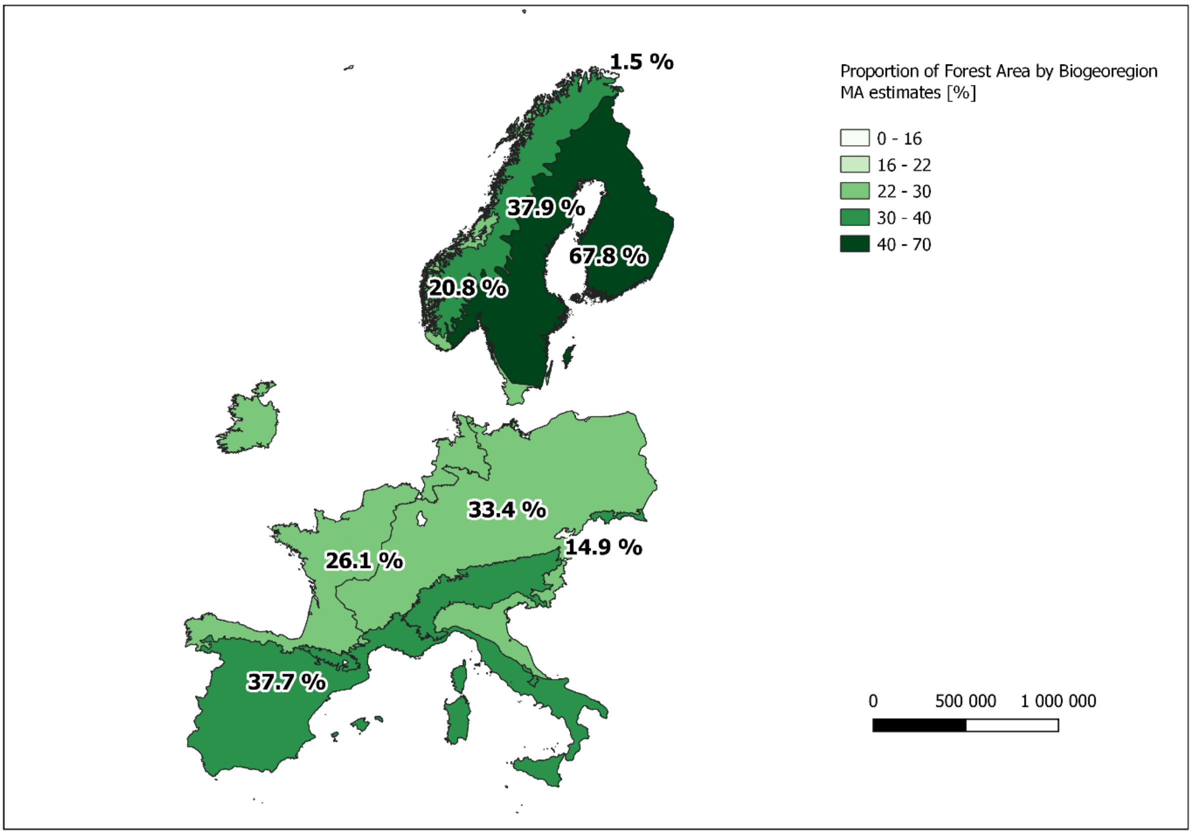


*Figure 4: Model-assisted (MA) estimates of proportion of forest on the area of biogeographical regions of Europe (14 European countries, 2020)*

The remaining target parameters (change of above ground biomass, forest that remained forest compared to previous inventory, gross and net annual increments and their corresponding domain, and deadwood biomass) are going to be estimated in the remaining period of the demonstration (until February 2026).

# 5. Dissemination and communication module demonstration

## 5.1 Demonstration item

The demonstration of the *Dissemination* module consists of the following item:

1. PathFinder portal for data download and visualization

## 5.2 PathFinder portal

The main purpose of the PathFinder portal is to enable easy access to the PathFinder mapping and estimation platform output product (i.e. maps and estimates). A demonstration portal was set up to illustrate the features that such a dissemination portal could have in an operational setting. Most importantly, the demonstration portal contains two key features:

1. Online visualization of maps, estimates, and forecasting scenarios
2. Dataset downloading

The online visualization interface enables users to visually explore the map and estimate output products. The portal can be accessed at: https://portal.pathfinder-heu.eu/. The user interface is illustrated in Figure 5. The map visualization features allow users to view and download selected map layers. The visualization of the estimate output products can also be viewed in map format in the selected spatial grid. Furthermore, figures of attribute statistics can be viewed by clicking the estimation grid cells.

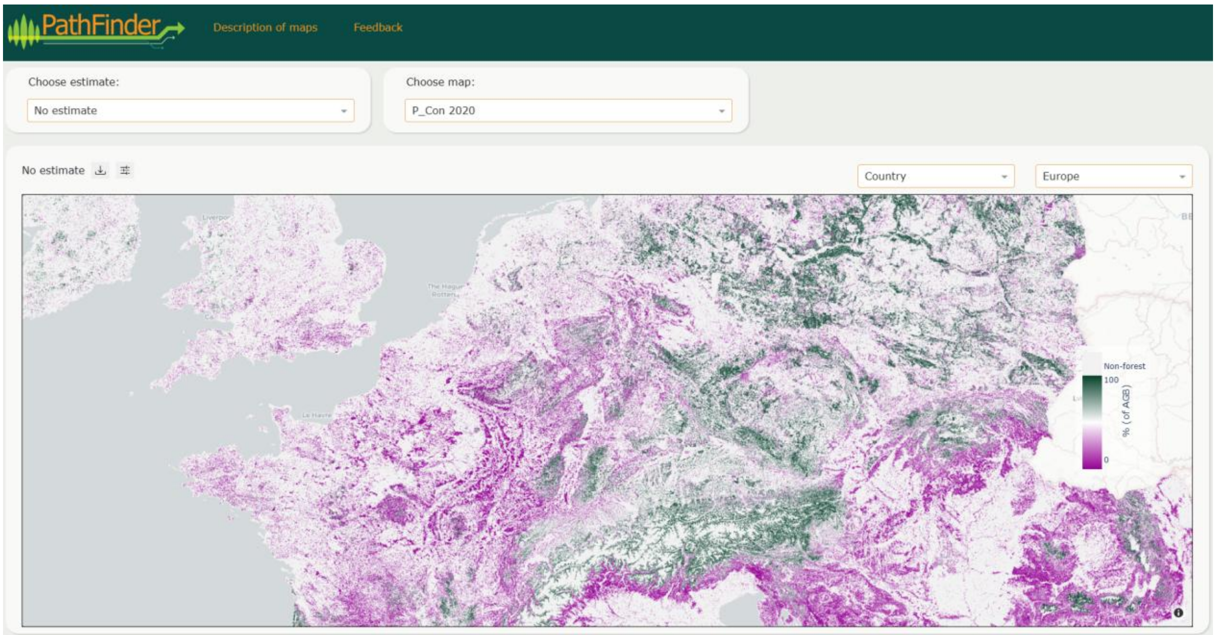


*Figure 5. Visual appearance of the PathFinder dissemination portal interface. (under development)*

The database of the PathFinder mapping and estimation platform output products can also be accessed through SFTP protocol with the following credentials:

- IP-address 46.60.23.191
- Port 22
- Username: *[provided by request sent through the visualization portal]*
- Password: *[provided by request sent through the visualization portal]*

Through this SFTP access, users can browse all the output files and supporting documents with their SFTP client. The download tool provides an easy way to download large quantities of the PathFinder output products. Links to the documentation of the technical characteristics of the products will be provided on the portal as well. All the maps follow the technical specifications listed in Table 3.

*Table 3. Output map technical specifications.*

| Feature | Specification | Notes |
|---|---|---|
| Spatial resolution | 10 m | Provided in 500 x 500 km tiles |
| Projection | EPSG:3035 -ETRS89-extended / LAEA Europe | |
| File naming | Final_demo_[YEAR]_[VAR]_E[xx]_N[yy].tif<br>Final_demo_[YEAR]_stdev_[VAR]_E[xx]_N[yy].tif | [VAR] refers to variable codes (Miettinen & Breidenbach 2025b)<br>[xx] and [yy] refer to lower left corner of the grid tiles. |
| File format | UInt16 | |
| Mask Values | 32766:  Non-forest<br>32767: No data | |

An important feature of the PathFinder mapping and estimation output products is that they are provided in formats that follow the Open Geospatial Consortium (OGC) standards. This allows easy integration of the output products to other databases by users. The maps and estimates could be made available for example though the Forest Information System for Europe (FISE), the Copernicus Data Space Ecosystem (CDSE) or other similar data storage and analysis platforms. Similarly, interested users (for example NFI agencies in European countries) would be able to download and integrate the datasets as part of their analysis and reporting process.

# 6. Discussion

A prototype of a European forest monitoring system has been demonstrated during the PathFinder project. This shows that relying on existing NFI data and newly developed methods, harmonized pan-European information on forests can be provided to support policy processes. The flexible implementation approach leaves room for further development within the platform modules and for the operational implementation of the system. While this deliverable has a focus on the mapping and estimation of the status quo, deliverable 3.5 (planned publication date July 2026) will have a focus on forecasting and scenarios which is another essential requirement for making informed policy decisions.

The choice to use k-NN mapping method in the demonstration was mainly guided by constraints related to computational complexity, reproducibility, harmonization and statistical considerations. One of the key constraints was that all the EO datasets used in the demonstration needed to be downloaded by all NFI partners for extraction of values in the plot locations. Although not as accurate as more sophisticated machine learning methods, k-NN performed robustly and transparently for continental level mapping. It is operationally fast, which was important for the final demonstration where 18 map layers (with the standard deviation layers) were produced. Adding EO features (in addition to the Sentinel-2 bands), was considered but the expected marginal improvements in the mapping accuracy achieved by including additional freely available EO datasets (see e.g. Teijido et al. 2025) were not considered worth the massive processing operations by NFI partners in extracting the values, as the main goal was to demonstrate the platform concept.

The k-NN method also enabled us to meet the strict requirements for statistical error metrics to be provided for all reference plots (leaving out primary sampling units in cross validation etc.). Statistical considerations were particularly important in the demonstration as the main purpose for the maps is to serve as auxiliary data for model-assisted estimation together with NFI plots. For all these reasons, the k-NN method with the Sentinel-2 was considered the most suitable option for the final demonstration mapping.

One of the main limitations for mapping was the uneven distribution of reference plots within Europe. The automated reference plot selection that used the 1500 nearest plots for each Sentinel-2 tile worked well in areas that had field plots available, but it caused clear artificial borders in the map in some locations where no plots were available. This was because the main sourcing area of the plots suddenly changed from one location to another. If the main sourcing area for a given Sentinel-2 tile was from southerly direction, but for the adjacent tile from northerly direction, the effects on the predictions may have been very clear, which could be seen as an artificial border in the map. But it is good to remember that in a truly operational setting, with most European countries joining the system, this would not be a problem as reference plots would be available more evenly around Europe. Regardless of these limitations of the mapping approaches, the resulting maps demonstrate the potential of integrated use of EO data and NFI plots.

After obtaining the NFI data from countries, the estimation part of the platform (nFIESTA) is capable to produce all desired estimates in a very short time frame. The combination of NFI field data and the auxiliary variables derived from maps (such as Copernicus) by means of model-assisted (MA) estimation (Adolt et al. 2018) led to notable reductions of standard errors of estimates of total forest area or above ground biomass. Similar effects can be expected for total of any other attribute defined within forest. The improvement of MA estimation of totals is to a large extent the result from the reduction of uncertainty with respect to forest area well captured by the Copernicus maps. Areas outside forest (also sampled by NFI plots) do not contribute to totals of target parameters defined within forest. Unlike forest management inventories, the NFIs do not operate within forest mask only, as the forest area itself is one of the target parameters to estimate.

For total above ground biomass, the ratio of standard error of Model-Assisted estimator (MA) to the standard error of the estimator using Field data Only (FO) is shown on Figure 6. Highest precision gains are observed for countries applying uniform sampling designs (Germany, Poland, Sweden, partially Finland and Austria), i.e. for countries that do not adjust sampling density in relation to the anticipated occurrence of forest resource in particular regions. In stratified, multiphase, or importance sampling the auxiliary information is used already at the stage of sampling, so there is not much room left for improvement if principally a very similar auxiliary variable is used in model-assisted estimation. This is the case of Italy (three-phase sampling design, with successive use of the information of the earlier phases to optimise sampling in the next phase), Spain and France (complementing the field sample by the first phase non-forest plots), and Norway (stratification according to altitude). Specifically in Czech Republic, the improvement is only moderate, still practically significant.

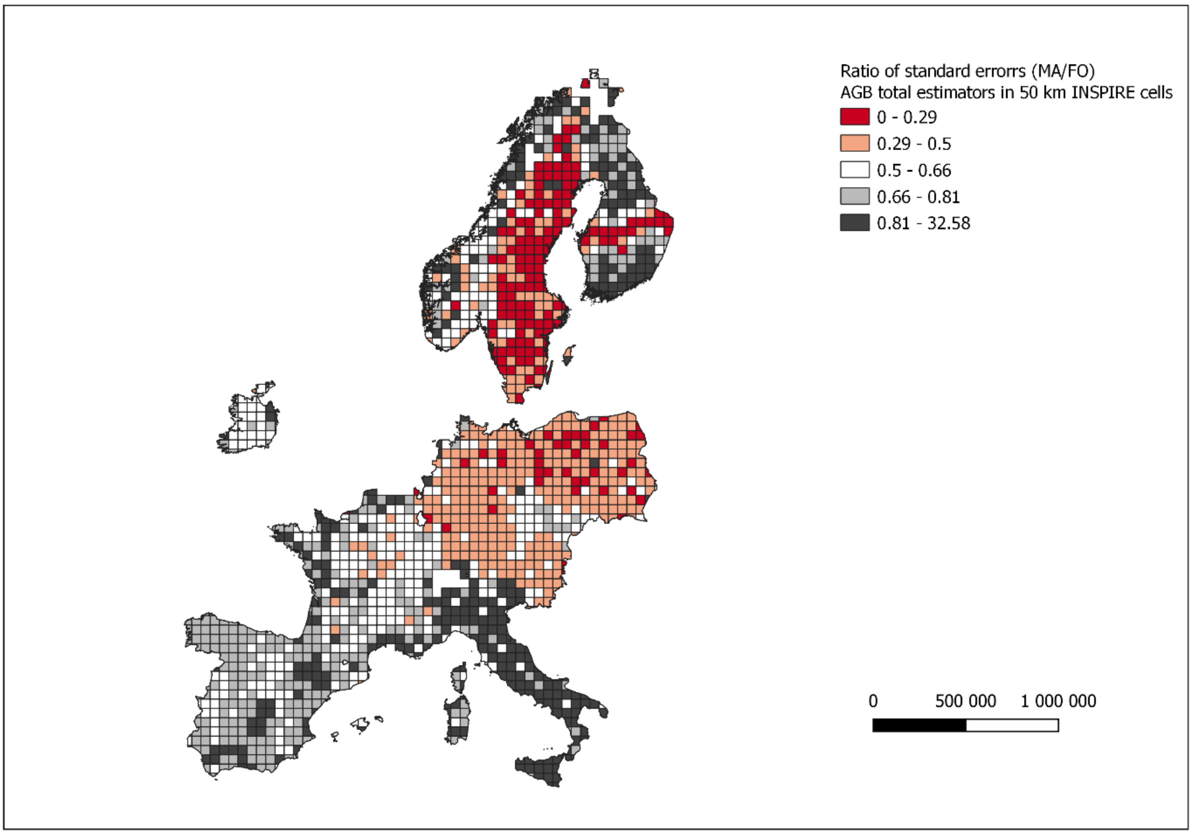


*Figure 6: Ratio of standard errors of the model-assisted (MA) and field-only (FO) estimators, total AGB (14 EU countries, 2020)*

By a closer look at Figure 6, one can notice a gap in Switzerland. This is because the standard error of the FO estimator was zero (most 2020 panel plots in these 50 km cells are outside forest and all have zero AGB), so the ratio was undefined. Here the model-assisted estimator is clearly of an advantage – it delivers a plausible, non-zero estimates of total AGB and its standard error, both are practically (asymptotically) unbiased.

The precision gains were not so large for per hectare values and ratios. This is explained by the cancelation of the sampling error of forest area between the numerator and denominator of the ratio which happens even for estimators using field data as the only source. Therefore, significant precision gains of ratios through model-assisted estimators are achievable only if the auxiliary information reduces sampling error within the forest mask. This is not the case of Copernicus Forest Type applied for model-assisted estimation of per hectare AGB (without distinction of species). The Copernicus Tree Cover Density has slightly better potential in this regard.

The estimate of AGB for the set of 14 European countries that provided their NFI dataset is shown in Table 4 below. The standard error corresponds to 0.5 % of the total estimate in both years and the standard error of difference (assuming independence of estimates between 2019 and 2020) is 1.5 larger than the estimated difference. One can conclude that the indirect model-assisted estimates of change are relatively precise, with standard error below 1% of the estimated total AGB. This suggests that a 2 % annual change of AGB could be detected with probability higher than 95%.

*Table 4: Estimates of total AGB, for the 14 EU countries, 2019, 2020 and their difference*

| Period | Estimation cell | Total AGB | Standard error | Variation coefficient | Actual sample size |
|---|---|---:|---:|---:|---:|
| 2020 | EU 14 countries | 14089 | 67.56 | 0.5% | 582651 |
| 2019 | EU 14 countries | 14026 | 67.65 | 0.5% | 582277 |
| difference | EU 14 countries | 63 | 95.61 | 151.8% | |

Only eight out of the 14 countries provided data for the years 2019 and 2020. The remaining countries contributed with the same data to estimates for both years. It is likely that the estimated difference of AGB between the two years would increase if data of all countries were up to date. Hower, the standard error of the totals and their difference might change only insignificantly due to the negligible change of the spatial variance of the population itself. The variation coefficient might further drop if all EU countries were included. Additional precision gains could be achieved by:

- changing Copernicus 2018 FTY and TCD for other maps with better temporal match and higher correlation with the AGB field data (for example the maps produced by the mapping part of the PathFinder platform)
- incorporating past NFI panels as auxiliaries through two-phase estimation
- relaxing the requirement for truly annual change estimation – moving windows averages might increase precision at the expense of acceptable trend smoothing

New two-phase estimators combining maps and past inventory data as auxiliaries, and estimators of their ratios and differences were formulated in deliverable D2.3 of PathFinder (Adolt, 2025).

Model-assisted estimators combining NFI data of EU countries have potential to detect annual AGB changes as small as two percent, or even smaller. Such a level of precision is comparable with errors of field measurements, allometric models (prediction of volume or biomass of sample trees) or sampling frame imperfections (the frame may deviate from the country’s actual territory) that cannot be ruled out entirely.

The data preparation by countries in the form of CSV files has been identified as a bottleneck and it cannot not be attributed to the first-time experience with the nFIESTA data format. The CSV data must be well structured, described by metadata and compliant with series of constraint assuring quality and error-free calculation of statistical estimates. The CSV format may not be the optimal way of NFI data exchange in an operational setting, because of the overall complexity of data and checking procedures. The alternative approach of connecting nFIESTA directly to the country's NFI data warehouse described in D2.1 seems preferable in the long run.

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