EFI Network Fund Report

Towards more flexible and improved European Forest Information and its governance structures

Summary and take-home messages of the EFINET project

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1. Introduction

Increasing pressures on forests in Europe are accompanied by a rapidly growing number of forest-related policy targets from the European Union (e.g. halting biodiversity loss and protecting 30% of the land, restoring 20% of EU land) as part of the European Green Deal and international conventions (e.g. Kunming-Montreal global biodiversity framework 2030). This stresses the importance of accurate, timely, and more detailed information on European forests as a basis for their sustainable management. Although a large amount of data is gathered from multiple sources, their combined use and harmonization remain difficult.

Data collection on forests across European countries varies significantly in terms of definitions (standards are rare and national definitions differ one from the others), formats (e.g. design-based estimates and maps from remote sensing), and timeliness (continuous vs. periodic data collection). These discrepancies make it challenging to compile reliable and comprehensive data on forests for the whole of Europe. Furthermore, the analysis of these datasets can yield diverging outcomes, depending on definitions applied or datasets used to answer to similar policy questions (e.g. the status of forest conditions in Europe). As a result, issues related to data availability, accuracy, and interpretation can lead to conflicting perspectives, potentially undermining the credibility of decision-making processes related to forests in Europe.

A harmonized, reliable, and timely European Forest Monitoring System is essential to effectively track the implementation of policies at the national and EU levels, and for fulfilling international commitments related to forests. Achieving this goal requires an improved, interdisciplinary approach to forest data collection and analysis.

The European Forest Information NETwork project (EFINET) had the following two aims:

1. Developing a conceptual framework and institutional environment required for the 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 the European level.
2. Applying the proposed approach in selected test areas across Europe to evaluate the applicability of the method.

To achieve these aims, the EFINET project conducted a review of European forest monitoring systems and stakeholder needs (Work Package, WP 1); this was followed by proposing a prototype of the European Forest Monitoring System, tested in five test areas in Europe (WP 2). Finally, different options for access and governance regarding European forest data were presented (WP 3) (see Figure 1).

Almost in parallel with the EFINET project, the European Commission released a legislative proposal for a Forest Monitoring Regulation which should fill existing gaps in the information on European forests and create a comprehensive forest knowledge base (https://environment.ec.europa.eu/topics/forests/forest-monitoring_en). Box 1 shows the list of variables for which the European Commission expects EU Member States to provide the data.

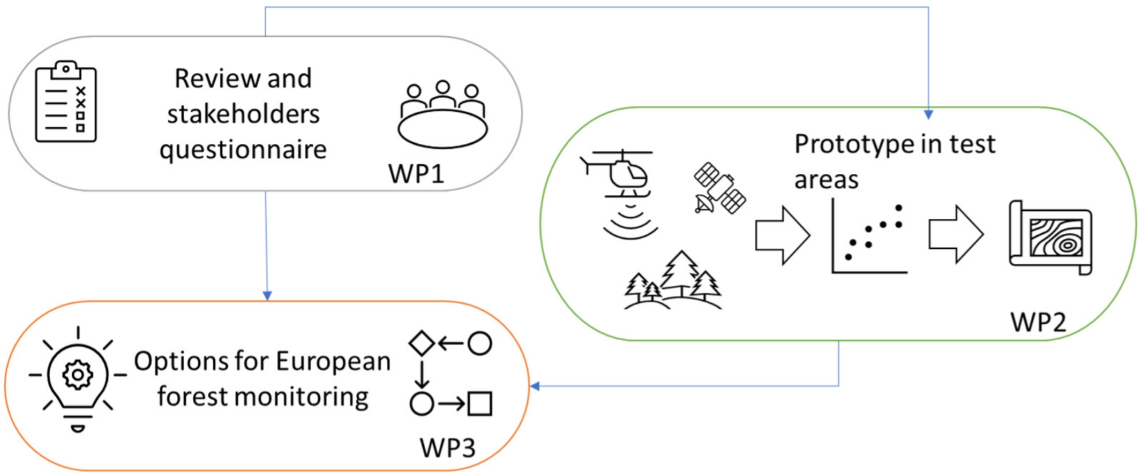

Figure 1. The EFINET project consisted of three interlinked components (WPs).

Forest indicators to be collected by Member States proposed by the Forest Monitoring Regulation in its Annex II.

The forest data collection framework in the Commission proposal for a Regulation for a monitoring framework for resilient European forest mentions the following variables to be collected by Member States (see Article 5(3)):

"Member States shall collect the following forest data, in accordance with the frequency specified in Annex II:

(a) *forest available for wood supply and forest not available for wood supply;*
(b) *growing stock volume;*
(c) *net annual increment;*
(d) *stand structure;*
(e) *tree species composition and richness;*
(f) *European forest type;*
(g) *removals;*
(h) *deadwood;*
(i) *location of forest habitats in Natura 2000 sites;*
(j) *abundance of common forest birds;*
(k) *location of primary and old-growth forests;*
(l) *protected forest areas;*
(m) *production and trade of wood products;*
(n) *forest biomass for bioenergy."*

In addition, there are other articles specifying resolution, temporal aspects, and additional indicators.

Box 1. Proposed Forest Monitoring Regulation, Annex II (COM(2023) 728 final) is available at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023PC0728. At the time of writing this report, the monitoring regulation is still very much under discussion with countries proposing a drastically changed version.

2. Challenges for forest monitoring systems and data needs

2.1. Current situation: Fragmented data and limited data accessibility

Data collection and access

The main part of information on European forests is provided by National Forest Inventories (NFIs), collected by countries. Despite its valuable contribution, ground data alone presents some limitations including cost, standardization issues, infrequent updates, and data access restrictions. See Box 2 for a short introduction to the NFIs standardisation/harmonisation process.

The exact locations of permanent NFI plots are not publicly available because securing the integrity of the plots preserves the reliability of statistical estimates. However, this information may be an essential component for research activities. In some of the EU countries the exact plot location can be accessible for research activities external to the NFIs while in other countries this information is available only for internal NFI use.

The use of remote sensing products alone for mapping forest properties has large limitations with increasing uncertainty moving from global to local scale levels. Also, they are mostly confined to produce spatial data on forest cover, forest cover changes and, considering the use of Airborne Laser Scanning (ALS) technology, tree height or vertical structure. The combination between remotely sensed data from active or passive sensors, thematic spatial products derived from raw remotely sensed data (such as the multitude of products available from the Copernicus services) and other sources of data (e.g. NFIs, ICP Forests, terrestial laser scanning) are frequent in research projects, and the number of research groups active in this area in Europe is high and increasing.

Many NFIs are multi-source inventories that incorporate remotely sensed information. However, their use is mostly limited to assess land cover and land use, and to determine the stratification of sample designs. Only a few NFIs produce spatially continuous estimates (maps) of forest variables integrating remote sensing data and field observations. Most other types of inventories, experiments, and other remotely sensed information produce a very separate data stream, which is mostly aimed at scientific products or models. With the support of various research projects, the NFIs are testing the new Forest Inventory, Estimation and Analysis “nFiesta” framework (https://gitlab.com/nfiesta) for calculating harmonized estimates across EU countries, as well as potentially for combining field with remotely sensed data while avoiding to share exact NFI plot locations.

Some efforts have been successfully made to develop pan-European assessments and capabilities based on detailed plot level and tree-wise NFI data, e.g. in the Wageningen University & Research developed European Forest Information SCENario (EFISCEN) modeling group (https://www.wur.nl/nl/project/european-forest-resource-analysis-tools.htm) and in EU-funded projects such as ForestPaths (https://forestpaths.eu), Pathfinder (https://pathfinder-heu.eu), DIABOLO (http://diabolo-project.eu), MoniFun (https://www.monifun.eu) or FORWARDS (https://forwards-project.eu). In these projects, combining NFI and remotely sensed data is demonstrating the advancement towards operational methods for pan-European forest monitoring systems.

Standardisation and harmonisation in European NFIs

National Forest Inventories are responsible for producing official statistics in almost all the EU countries. The methods used (both in the field and for statistical calculations) may be different within Europe because they were optimised by the countries on the basis of local conditions. There are also differences in defining the variables to be monitored (e.g. even the definition of "tree" varies by countries). NFIs cooperate in the framework of the European National Forest Inventory Network (ENFIN) to reduce such differences to be able to aggregate statistics provided by the different countries to produce European figures. This is possible only if the countries adopt same definitions of the variables to be estimated, even if the methods for the estimation are different. When the definition of a forest variable is agreed internationally, we refer to it as a "standard". Currently only one standard is agreed across (most) of the EU NFIs: the definition of "forest" presented for the first time by FAO in the framework of the Global Forest Resource Assessment programme. Thanks to this agreed standard, we can aggregate the forest area estimations provided by the different countries to estimate the forest area for the whole Europe. The process of standardising all the variables acquired by the NFIs is more complex. If the NFIs change their own definitions by adopting an agreed definition, they risk losing the comparability with previously acquired data. Methods for adopting multiple definitions also exist but in most of the cases they are expensive as they require more time in the field and/or more complex calculations. The methods to transform existing data already acquired by the NFIs with different definitions to produce new estimates referred to a common agreed definition are frequently called "harmonisation". For this reason, the different activities to move towards the possibility to use European NFIs to report consistently at a European level are frequently referred as a process of "standardisation/harmonisation".

Box 2. The concepts of standardisation and harmonisation in the NFIs.

Reporting: Inputs for international reporting (e.g. FAO, UNECE, EEA, Eurostat, FOREST EUROPE) are provided by each country based on e.g. NFI data and national processing routines. Processing routines are semi-open (e.g. available in published documentation only on EEA FISE). Outcomes are reported as aggregated results at the national level, making them nearly impossible to relate to local contexts. Additionally, different institutions can report different values for the same variable and reporting years. For example, the data provided by FOREST EUROPE (the former Ministerial Conference on the Protection of Forest in Europe) in the State of Europe's Forests (SOEF) on forest fires are strongly inconsistent with the data provided by the European Forest Fire Information System (EFFIS) of the Joint Research Centre of the European Commission and nowadays incorporated in the Copernicus Emergency Management System (https://forest-fire.emergency.copernicus.eu/). A comparison between SOEF and EFFIS data for the three EU Member States more affected by forest fires reveals that while in Spain annual figures are almost identical (apparently EFFIS data were adopted for FOREST EUROPE reporting), in Italy and Greece the values reported in the SOEF are inconsistent with EFFIS, most probably because derived from local monitoring systems (Figure 2). In general one can state that the reporting to FOREST EUROPE is too voluntary leading to inconsistencies, incompleteness and rather outdated data. In the end making the whole (costly) effort not very useful.

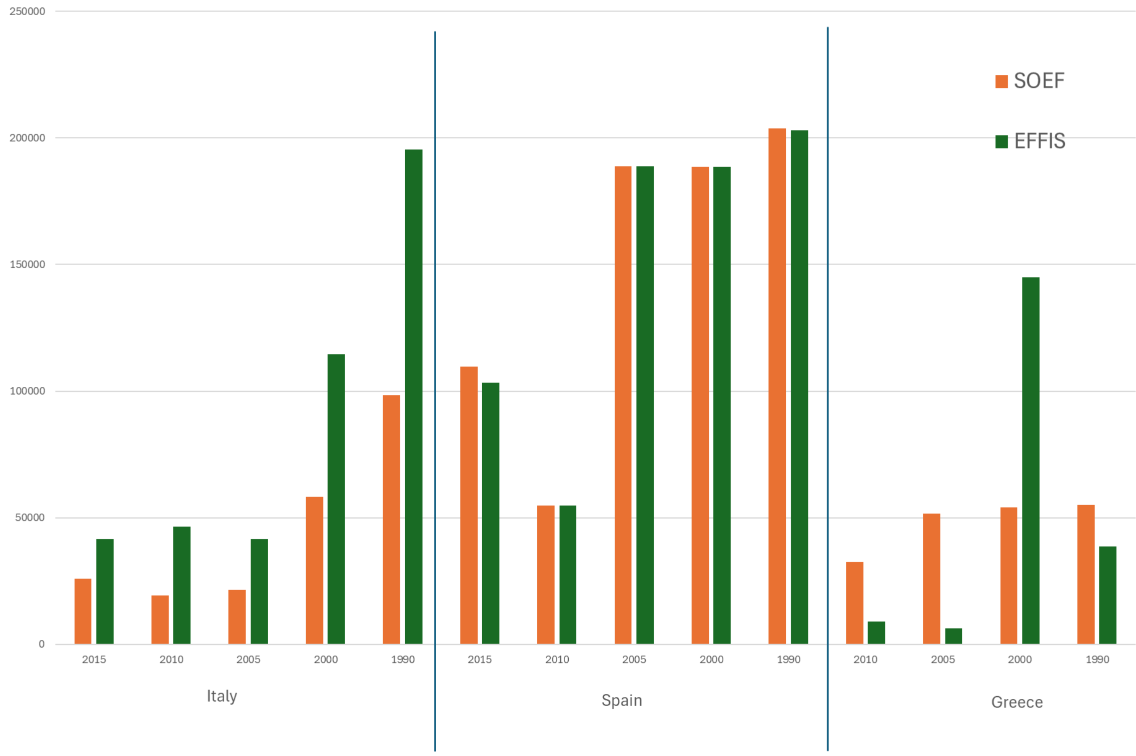

Figure 2. Comparison between the area affected by forest fires in Italy, Spain and Greece between the data of the State of Europe's Forests (SOEF) and those from European Forest Fire Information System (EFFIS). Values in hectares.

2.2. Which data are needed? A user perspective based on the EFINET survey

Although several user studies have been carried out (e.g. on Earth Observation applications), views and needs are still rapidly evolving because of different policy objectives and the advancements of new technologies. Therefore, we conducted a new survey, and expert meetings to determine data needs, gaps, and possible improvements in the context of forest monitoring in Europe. For the full analysis of the data obtained in the survey and during the meetings, we refer to the extended version of the EFINET report, while the main results are summarised here below. In Box 3 we recalled some of the basic principles of forest estimation and mapping.

Data needs: The relevance of open-access, ground-based reliable statistics aggregated over large regions, as well as accurate thematic maps from remotely sensed data was emphasized by the involved experts as an essential component for forest monitoring. Confirming the importance of traditional variables in forest monitoring (such as forest area, carbon stock, biomass, and timber volume both as figures at a certain time and as changes such as volume increments, and loss/gain of forest area), along with other variables, such as wood harvesting, CO_2 removals, biodiversity, and disturbances as well as more novel indicators on forest multifunctionality (including social aspects). The role of NFI data in producing such information is strictly related to their level of accessibility and standardization. Future improvements in this direction should result in more support for NFI programs. The analysis carried out in EFINET also resulted in the identification of challenges in combining EU-level data, especially ground-based information, due to the variation of definitions and methods used across the European NFIs.

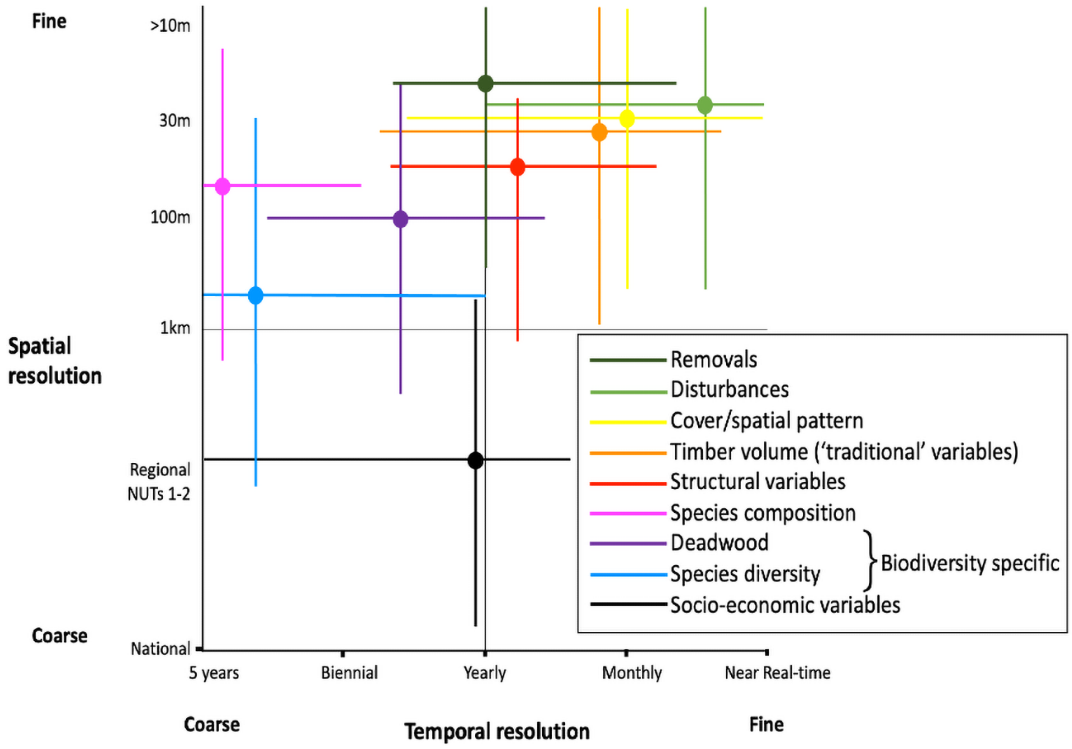

Figure 3. Results from the EFINET survey: the main forest variables and their desired spatial and temporal resolution are indicated by a central dot, with their ranges expressed by lines.

Preferences in **spatial resolution** availability varied based on the specific forest variable, with finer resolutions preferred for traditional variables: wood removals, structure, and forest composition (10 m; relying on remote sensing), and coarser resolutions for mapping biodiversity and disturbances, spatial patterns, or socio-economic variables (30 m to 100 m, and up to regional levels) (see Figure 3).

Data gaps were identified regarding establishing standardized data formats, indicators, and aggregation levels to ensure consistency and comparability across various datasets. In this context, the integration of remote sensing and ground data was seen as representing a valuable opportunity to provide a spatially consistent pan-European monitoring scheme. Remote sensing optical data alone was still seen as having large challenges, as it can only provide information for certain forest variables, mainly related to forest cover. However, linking these observations to models may offer new methods for quantifying key variables such as forest disturbances.

Forest data availability (NFI in particular) as a key element to ensure transparency and comparability across countries, was underscored in the discussion with experts and stakeholders. The discussions highlighted a need for a framework that considers both the privacy needs of the NFIs and the public's right to access environmental data acquired by public bodies. Developing protocols and data access mechanisms that allow seamless data flow and interoperability between these initiatives (and adhere to privacy rules) is vital for a comprehensive and cohesive European Forest Monitoring System. Such a framework needs to be based on the collaboration between forest stakeholders and policymakers.

Finally, **optical satellite imagery** emerged as one of the most relevant types of remote sensing data, closely followed by ALS. Radar-based assessments are still being developed but could offer promising possibilities (depending on the radar frequencies used by the sensors).

Estimating and mapping forest variables

First it is important to recall the principles used in the NFIs to create forest statistics, that are usually adopted as the only official assessment of forest resource in a country. Since it is not feasible to measure all the trees of a forest, in the NFIs the principles of *inferential statistics* are used. From the population of all the forests (and all the trees in the forest) a sample is extracted based on a formal sampling design, all the NFIs adopt a systematic sampling design. The measures are carried out in the sample and the results are then inferred to the population with functions called *estimators*. The most used family of estimators are called Horvitz-Thomson (H-T) estimators from the original publication of these authors from 1952 “A generalization of sampling without replacement from a finite universe” appeared in the Journal of the American Statistical Association. This is the reason why the results of the NFIs are called *estimates* (they are also referred as *design-based estimates*, because the sampling design is the only needed prerequisite needed for the application of the method, contrasted to *model-based* estimates that are instead based on the validity of a model). The real true values remain always unknown (it is known only when all the trees of a forest are measured), but since the sampling design is somehow based on randomness (it is possible to formally calculate the probability of inclusion of each element of the population in the sample) it is thus possible to associate a confidence interval to the estimation. So for example on the basis of the NFI in Italy for the year 2015 we cannot know the exact number of trees but instead we can say, with a probability of the 95%, that the total number of trees is between 11,645,154,204 and 12,254,107,390 or, in other words, that the total number of trees is estimated equal to 11,949,630,797 with a standard error of 1.3%.

With the advancement of Earth Observation technologies since the late 1970s, scientists have started developing various techniques to map forests, their health status, composition and quali-quantitative characteristics. Research efforts explored various directions. Firstly, creating simple binary forest/non-forest maps and then trying to classify forest in various categories based on main tree species composition and then trying to track forest area or tree cover trends in time, resulting in different types of disturbance mapping efforts. A specific area of application was directed towards the integration between NFI plot level observations and spectral information from passive optical sensors first, and then from active sensors like radar and lidar. The result of this integration are again maps for the same variables that are estimated officially from the NFIs (growing stock volume and biomass are the most used) but with a spatial resolution that is much higher than that one available from traditional H-T design-based estimates. While the NFIs produce estimations for large regions (most commonly in Europe for Countries and NUT1 administrative levels), maps from remote sensing can nowadays produce predictions down to pixels of a few meters in resolution (or even for the single trees). But traditionally maps from remote sensing are not associated with a formal error estimation like official NFI estimates. Only recently the two scientific areas (statistical inference on one side and remote sensing on the other) have demonstrated the possibility to integrate the two disciplines proposing many different hybrid approaches.

Box 3. The basic principles of estimations and mapping of forest resources.

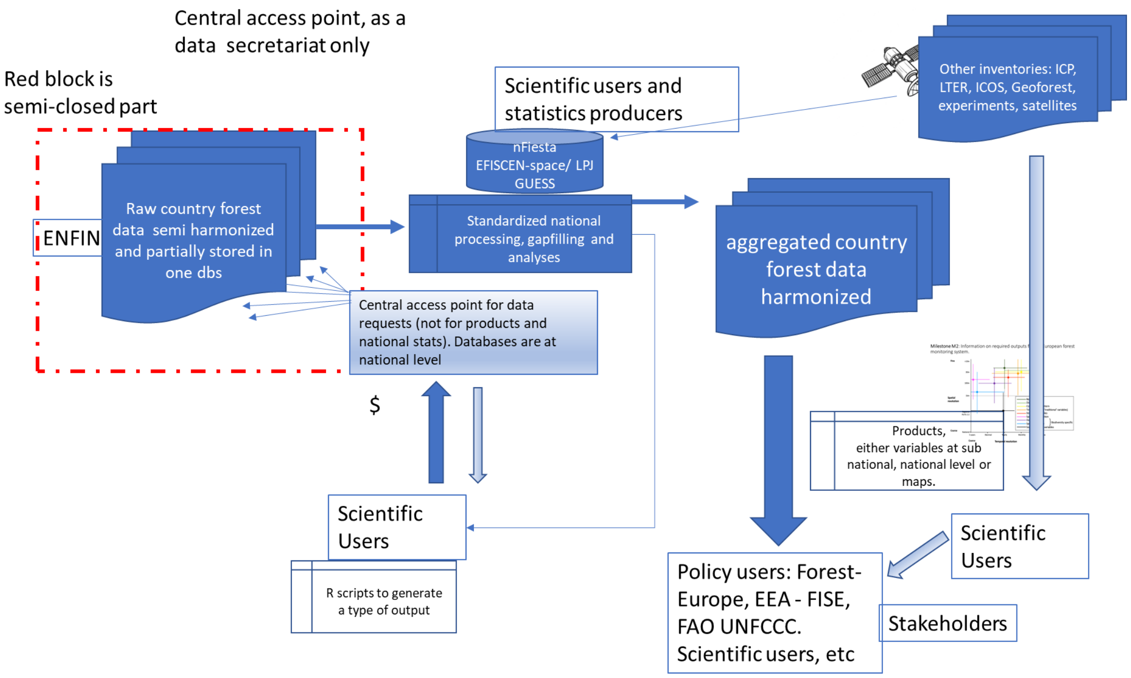

Figure 4. Envisioned process in the medium short term: central access point and standardized processing, modelling, and gap filling. Raw data stays at the country level. See Figure 5 for a more advanced system.

2.3. Way forward: a Central Access Point

While in EFINET we proposed several approaches for the possible implementation of a European Forest Monitoring System, in Figure 4 we outline a workable option for the medium short term option for an operational and feasible process to improve the current situation. Collaboration between experts (mainly from NFIs), science and policymakers (e.g. European Commission), is key for creating a data access protocol (see e.g. https://forestplots.net/en/join-forestplots/code-of-conduct) with a **Central Access Point (CAP).**

The CAP would collect data access requests and data use plans and forward them to NFIs to obtain acceptance similar to the process currently followed by ICP Forests and the Global Forest Biodiversity Initiative (Figure 4). Next, the NFI data or derived products are provided to the user according to a user agreement on a project basis. The results of the project, research or other, would then be made available for open access (e.g., derived data products) with an iteration round by countries. To reduce the workload of NFIs, the system could gradually develop in the next 5–10 years into a more centralised and harmonised database (Figure 5).

The **six advantages** of the proposed way of working are:

(i) streamlined and clear data access for all NFIs and easier and systematic data access for external data users;
(ii) pre-determined and transparent data use policies;
(iii) pre-processed data by the NFIs could reduce potential errors by users, preferably a form of harmonization in storage would be needed;
(iv) small steps towards databases at NFIs that are partially harmonized and easier, or there are bridge functions to harmonize;
(v) raw individual-tree data are available in principle, but data providers maintain control over access; and
(vi) by definition the central access point is open to all requests.

This proposed way of working has also the following **five drawbacks** to be considered:

(i) its success heavily relies on the efficiency and responsiveness of the CAP;
(ii) individual NFIs still have the right to decline data requests, and some countries may continue to resist granting access to their data, potentially hindering the effectiveness of a centralized approach;
(iii) Harmonizing data using appropriate procedures remains a crucial factor. However, this poses the challenge that changes in NFI designs may result in heterogenous information and inconsistent data with previous years. Therefore, it is essential to develop designs that ensure both the seamless continuation of time series and the facilitation of transnational harmonization;
(iv) calibration of remotely sensed data may be still contingent upon NFIs agreeing to disclose precise plot locations to specific groups, which might raise privacy and confidentiality concerns;
(v) extra costs are incurred due to the need to establish and maintain an infrastructure for the CAP, which implies a need for stable financial support. Moreover, creating conversion procedures for the national databases into the standardized format requires additional resources from the NFIs, leading to the necessity of holding a second copy of the database in the common format. This process could be lengthy and may require international collaboration or long-term support.

The CAP could then gradually improve in its capacity and mandate playing an **analytical and central database role**. This means it could also include data access protocols and have a stronger directive role leading to harmonization of stored data and in the long term possibly some influence on inventory standardisation of approaches and designs. This requires an integrated use of additional data streams and a role for FISE, ENFIN, JRC, EFI, or a core group of NFIs. The focus is put on open-data policies and fully harmonized/processed data in one database including raw data, with agreed data access rules. So that data can also be made accessible to all stakeholders, including forest owners and managers.

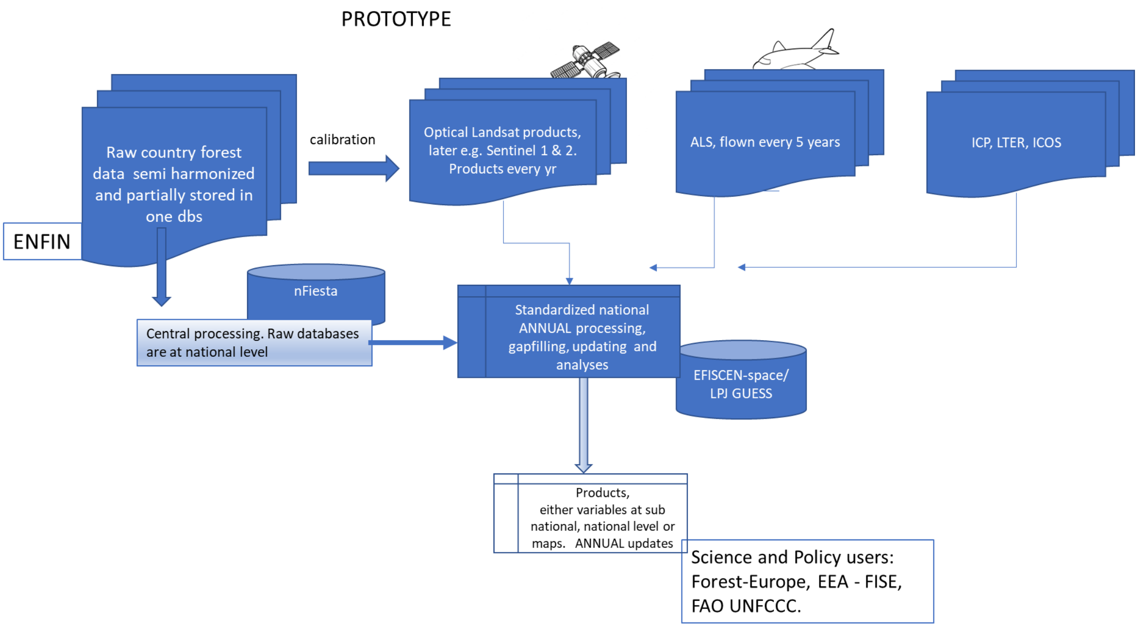

Figure 5. Design of a possible prototype of a near real-time European forest monitoring system building on Figure 4, providing annual updates of main forest variables at high and medium-high resolution.

3. A component tested: remote sensing complementing ground-based information

In EFINET a prototype component of the framework system for producing yearly spatially continuous estimates for a group of selected forest variables, was developed and tested in five case-study locations in Poland, Netherlands, Switzerland, Sweden, and Italy (Figure 6), in order to cover different climate regions, forest ecosystems, management types, orographic conditions, and information needs.

The system was tested for spatially estimating magnitude, persistence, and recovery trends of forest disturbances (Figure 6), from which information on forest height, biomass and growing stock volume, basal area, tree density, and canopy cover was derived. The prototype is based on the idea of maximizing the added value of satellite observations that are available with an open access policy at pan-European level with increasing temporal and spatial resolutions made available through the Copernicus program and the new Sentinel satellite missions.

The prototype is based on a hierarchical model-assisted approach where ground observations (from NFI or other sources) are used only in the last phase of the process. The method is based on the axiom that the best source of information for the wall-to-wall spatial estimation of forest variables is the data from ALS. It was already demonstrated in the literature that models based on forest height metrics calculated from ALS point clouds can produce precise estimates of compositional and structural forest variables.

Figure 6. The five test areas used in the EFINET project.

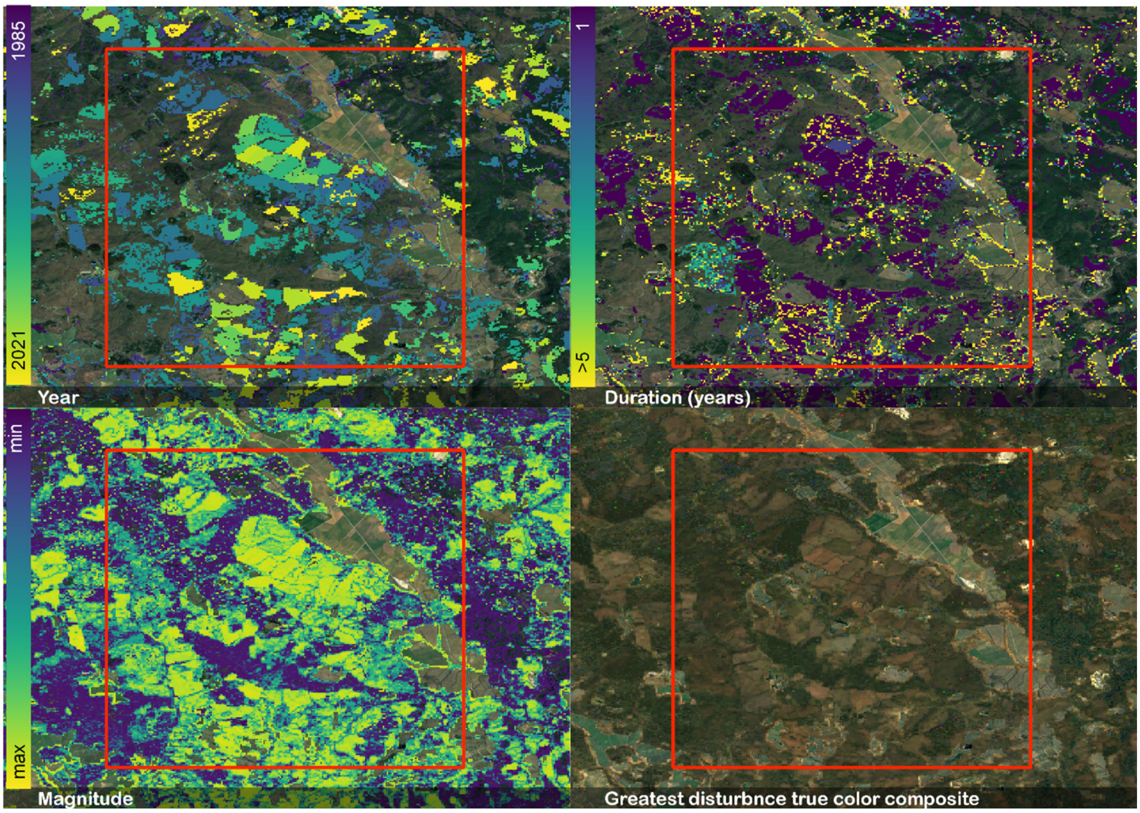

Figure 7. Example of forest change and metrics maps. The upper left panel shows the year in which the greatest disturbance of the time series occurred; in the upper right panel, forest disturbance duration is shown. The bottom panels show the magnitude of the greatest disturbance that occurred (left), and the true-colour composite of the greatest forest disturbances.

An optimal approach for monitoring European forests would be the availability of a periodically updated, wall-to-wall, pan-European ALS coverage. Such coverage would enhance forest inventories and enable the quantification of biomass loss caused by disturbances. However, this type of data is only available in certain regions of Europe that have established programs for regular ALS acquisitions.

To address this limitation, the EFINET approach focuses on generating forest height metric predictions using models where predictors are derived from the analysis of four decades of Landsat time series. This approach also allows for the prediction of disturbance severity and forest regrowth. Wall-to-wall predictions of forest height metrics are subsequently employed to estimate forest variables, with both steps leveraging a state-of-the-art AI method based on fully connected neural network (Figure 7).

This approach has **five benefits**:

(i) **Consistent and replicable**: forest disturbance maps and other compositional or structure forest variables are produced in a consistent way along the same computational process;
(ii) **Rigorous**: ground data do not have to come from rigorous statistical sampling design and data from different local dataset can be easily aggregated, if acquired based on same reference definitions;
(iii) **Harmonised**: local ALS dataset can be used, harmonized, and aggregated even if acquired at different dates, although different point density may result in different accuracies;
(iv) **Regular**: the system can produce regular yearly estimates independently of when and where ground data are acquired;
(v) **Scalable**: pixel-level predictions of the different variables can then be aggregated at different desirable resolutions or administrative levels to produce formal model-assisted estimates with relative confidence intervals.

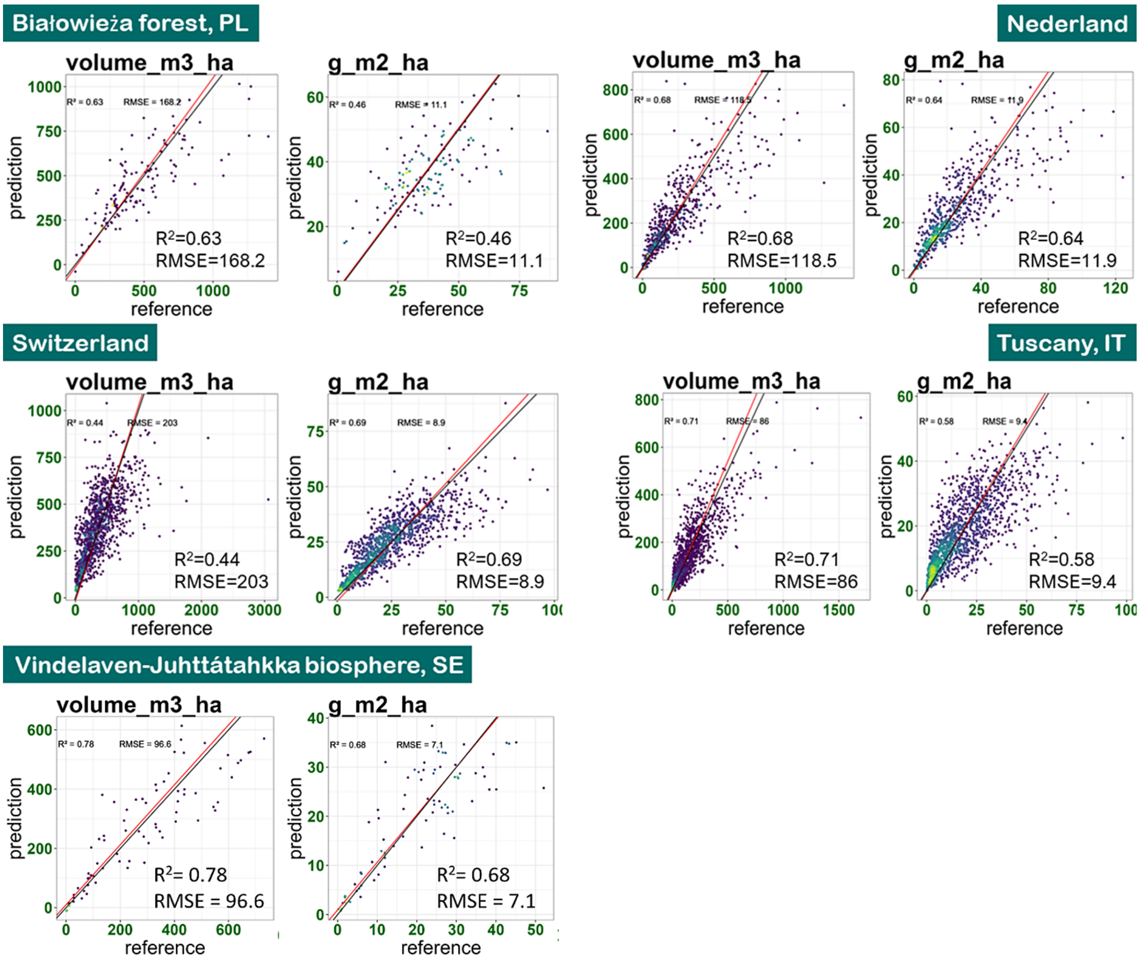

Figure 8. Pixel level accuracies in the five test areas of EFINET for growing stock volume and basal area.

In the five EFINET test areas forest height metrics were predicted using optical satellite data, which were then used to predict growing stock volume and basal area with satisfying final results (Figure 8). It is important to remember that pixel-level predictions are not the final product of the system, but pixels have to be aggregated for larger regions to produce statistically rigorous estimates and confidence intervals over administrative or forested regions (the so-called concept of “forest units”).

4. Conclusions

An enormous wealth of data useful for forest monitoring and assessment is being gathered both at the pan-European level and by the different countries. However, making use of these data and turning them into standardized (or harmonized) and usable information is often lacking and is only done rarely wall-to-wall across Europe, and mainly in the framework of research projects.

Challenges include harmonizing existing forest data, producing information closer to real time, standardizing NFI methods and definitions, and integrating ground surveys with remote sensing data. It is important to remember that traditional ground-based approaches can produce formal statistical estimates only for large administrative regions and are often unharmonized among the countries.

The integrated use of Earth Observation tools can provide spatially explicit information (e.g., 10 or 30-meter pixel level, or small area estimations), but often are limited to variables related to land cover or photosynthetic activity. In this context, ALS data can significantly contribute to expanding the availability of information and may be the basis for EU forest monitoring if properly complemented with satellite remote sensing data and artificial intelligence.

Moving toward a comprehensive, unique, and exhaustive European Forest Monitoring System will require strong momentum, demand from regulations, and funding. This centralization, harmonization, and step-by-step gradual standardization of the inventories themselves will not happen unless strongly driven by policy needs both nationally and at the EU level. Member States, NFIs, and the European Commission will have to collaborate in this effort. It will also require central and long-term funding which can start relatively small (see Figure 4) but will need to grow in collaboration with expert institutes and statistics providers (JRC, EEA, FAO) with NFIs (ENFIN), ICOS, and ICP Forests and remote sensing groups. Even then, harmonization of the inventories in the field, and the development of new techniques and methods to assess new variables and services (including socio-economic aspects) will require significant investment in Member States. This could sometimes be part of ongoing research and innovation funding. Some research funding should come from EU programs of Horizon Europe, LIFE Climate Change Mitigation and Adaptation, or the European Agricultural Fund for Rural Development (EAFRD).

EFINET also proposed a technical framework (Figure 5) easily adaptable to different local conditions as the parameters and thresholds of the system can be adjusted to deal with the different characteristics of different forest ecosystems or different forest management approaches. The integration of remotely sensed data with ground observations allows the production of more spatially detailed estimates of forest variables compared to that obtained by exploiting field data alone. In addition, while the presented framework requires ground data only for the final validation, it may be implemented at the EU level by requiring little effort and costs as it exploits open-access data and ready-to-use methods.

From the analysis of the different options for a possible implementation of the system, a more consistent involvement of key actors and stakeholders, coupled with the use of more technological advancements in big data analysis (such as the use of artificial intelligence), are essential to foster robust decision-making and adaptation of policies at a European level.

The prototype of the system could be structured as illustrated in Figure 5. It would provide annual updates of specific forest variables at medium-to-high resolution through the combined use of Landsat and Sentinel-1 and Sentinel-2 data, supplemented by ALS updates every 3 to 5 years and the most recent sets of ground-based measurements. To address data gaps, predictive models could be employed where necessary.

A central access point for harmonized NFI ground-based data would be a key prerequisite to streamlining the annual processing workflow. This could involve integrating pre-processed and quality-checked data into a unified database. Additionally, other relevant datasets, such as atmospheric data from ICOS, could be utilized to further enhance the system's analytical capabilities.

In summary, the outcomes of the EFINET project plot a pathway towards a harmonized pan-European forest monitoring system, combining ground-based and earth observation-based data, and contributing to answer to the challenging request recently presented in the proposal for a new European forest monitoring law.

5. Take-home messages

The results achieved in the different components of the EFINET projects can be summarised as follow.

- **Need for accurate Forest Statistics**: There is a critical need for accurate, timely, and detailed forest statistics, accompanied by formal error estimates, to support decision-making, especially given the growing pressures on European forests and the increased focus on forest-related strategies.
- **Challenges in Data Harmonization**: Harmonizing EU-level data is challenging due to existing differences in definitions and methodologies used to measure or estimate forest variables. Integrating Earth Observation and ground data is suggested to achieve spatially explicit and consistent products. Open-access, standardized data formats, and collaborative data access policies are essential.
- **National Forest Inventory (complemented by Remote Sensing)**: Forest statistics in Europe are mainly derived from NFI estimates aggregated for large administrative regions. Despite its valuable contribution, ground data alone presents some limitations including cost, standardization issues, infrequent updates, and data access restrictions. Remote sensing products alone also have large limitations (and are mostly confined to produce maps for some forest variables such as tree cover and tree cover changes and, with ALS, tree height) with consistent uncertainty. In this context, the complementary use of RS with ground based measures (from NFIs and other networks) can provide very useful spatially explicit information for single pixels (maps) or aggregated at different scale levels, as already practiced by some NFIs.
- **A periodic Forest Monitoring is optimal**: The optimal condition for monitoring European forests is a yearly wall-to-wall pan-European ALS coverage. Currently the real condition is far away from the optimal, with ALS data available just over limited regions and updated too infrequently, with disparate acquisition protocols (in terms of e.g.: pulse densities, flight-height, instruments used, pre-elaboration protocols, acquisition period in different phenological conditions). However, harmonization with satellite optical products could enhance monitoring by facilitating ALS data harmonization and wall-to-wall (yearly) coverage. The results obtained in EFINET demonstrate the possibility of such operational approach.
- **Next steps** required to move forward are:

  - **Enhance Data Accuracy**: The increasing pressures on European forests, also as a direct or indirect effect of climate changes, and the numerous forest-related policies stress the need for more accurate, timely, and detailed forest information for supporting future sustainable decisions.
  - **Integrate Data Sources**: Overcome challenges in harmonizing ground-based (from NFIs and other networks such as ICP Forests) and remotely sensed data to establish a comprehensive forest monitoring system.
  - **Fill Data Gaps**: Address significant gaps in reliable forest data to support credible European forest-related policies by creating a harmonized European Forest Monitoring System.
  - **Centralize Data Access**: Establish a Central Access Point for harmonized NFI data to streamline access, enhance transparency, and support consistent data processing.
  - **Standardize Data Formats**: Adopt standardized data formats and integrate remote sensing with ground data to provide spatially consistent European Forest Monitoring System.
  - **Integrate Remote Sensing**: Integrating remote sensing with ground data can provide spatially consistent pan-European forest monitoring, with optical satellite imagery and ALS playing crucial roles.
  - **Consider Adopting Regulations**, create funding, and strengthen collaboration. Achieving a comprehensive European Forest Monitoring System requires regulations, centralized funding, and collaboration among expert institutes, statistics providers, Member States, the European Commission, and other European bodies (such as the EEA, ESA, and the Copernicus services).

A harmonized monitoring pathway for Europe's forests EFINET outlines a pathway toward a harmonized European Forest Monitoring System based on:

(a) defining regulations (and required variables with their accuracy and timeliness), funding, and collaboration with expert institutes, statistics providers, and research funding programs.
(b) leveraging and developing operational combinations between remotely sensed information and ground-based (from NFIs and other networks) as a short-term solution to bridge gaps between field-acquired information and remotely sensed products from different countries.
(c) using and developing workflows for improved forest monitoring governance, featuring standardized intermediate databases, a Central Access Point, and a reference in-situ ground component. Such workflows have been developed in several EU-funded projects, in ICP Forests and in ENFIN.
(d) benefitting from an enhanced collaboration among actors involved in forest monitoring, reporting, and governance of data in Europe. Also expanding the cooperation with other monitoring networks to achieve a more comprehensive assessment of all the ecosystem services provided by forests (especially biodiversity and social values).
(e) To demonstrate a way in which the described problems could be addressed, EFINET has developed **a prototype system for spatially explicit predictions** of forest variables (mostly disturbance-related), integrating satellite observations, ALS, and in-situ data to provide consistent, yearly estimates at different granularities, addressing challenges related to ground data variability. The system has been demonstrated over five study areas across Europe, covering very different forest ecosystems and ensuring results generalizability.

6. List of Acronyms

AI:	Artificial Intelligence
ALS:	Airborne Laser Scanning
CAP:	Central Access Point
EAA:	European Environmental Agency
EAFRD:	European Agricultural Fund for Rural Development
EC:	European Commission
EFFIS:	European Forest Fire Information System
EFI:	European Forest Institute
EFINET:	European Forest Information NETwork
ENFIN:	European National Forest Inventory Network
EO:	Earth Observation
EU:	European Union
FAO:	Food and Agriculture Organization of the United Nations
FISE:	Forest Information System for Europe
FOREST EUROPE:	Ministerial Conference on the Protection of Forests in Europe
ICOS:	Integrated Carbon Observation System
ICP Forests:	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
JRC:	Joint Research Centre of the European Commission
MS:	Member Stated of the EU
NFI(s):	National Forest Inventory(ies)
RS:	Remote Sensing

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