Forest Ecology and Management 561 (2024) 121875

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Perspectives: Resilient forests need joint forces for better inventorying and monitoring

Marco Ferretti [a,*], Arthur Gessler [a,b], Nathalie Cools [c], Stefan Fleck [d], Rossella Guerrieri [e], Tamara Jakovljević [f], Manuel Nicolas [g], Tiina M. Nieminen [h], Diana Pitar [i], Nenad Potočić [f], Stephan Raspe [j], Marcus Schaub [a], Kai Schwärzel [k], Volkmar Timmermann [l], Monika Vejpustková [m], Lars Vesterdal [n], Petteri Vanninen [o], Peter Waldner [a], Lothar Zimmermann [j], Tanja GM Sanders [k]

[a] Swiss Federal Institute for Forests, Snow and Landscape Research WSL, Zürcherstrasse 111, Birmensdorf 8903, Switzerland
[b] Institute of Terrestrial Ecosystems, ETH Zurich, Universitätstrasse 22, Zürich 8092, Switzerland
[c] Research Institute for Nature and Forest (INBO), Gaverstraat 4, Geraardsbergen 9500, Belgium
[d] Northwest-German Forest Research Institute, Grätzelstraße 2, Göttingen 37079, Germany
[e] DISTAL, Alma Mater Studiorum – University of Bologna, Viale Fanin 44, Bologna 40127, Italy
[f] Croatian Forest Research Institute, Cvjetno naselje 41, Jastrebarsko 10450, Croatia
[g] Office National des Forêts, Département Recherche-Développement-Innovation, Boulevard de Constance, Fontainebleau 77300, France
[h] Natural Resources Institute, Luke, Latokartanonkaari 9, Helsinki 00790, Finland
[i] National Institute for Research and Development in Forestry "Marin Dracea", Eroilor 128, Voluntari, Ilfov, Romania
[j] Bavarian State Institute of Forestry (LWF), Hans-Carl-von-Carlowitzplatz 1, Freising 85354, Germany
[k] Thünen-Institute of Forest Ecosystems, Alfred-Möller-Str. 1, Eberswalde 16225, Germany
[l] Department of Fungal Plant Pathology, Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research (NIBIO), Ås 1431, Norway
[m] Forestry and Game Management Research Institute, Strnady 136, Jíloviště 252 02, Czech Republic
[n] Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, Frederiksberg C DK-1958, Denmark
[o] Natural Resources Institute, Luke, Vipusenkuja 5, Savonlinna 57200, Finland

ARTICLE INFO

Keywords:
EC forest monitoring framework
Existing monitoring resources
Monitoring vision

ABSTRACT

Forests are increasingly affected by global change. Building resilient forests requires – amongst others - leveraging the wealth of knowledge from existing ground-based, field inventory and monitoring programs as well as Earth Observation systems to better assess the status, detect changes, understand processes, predict future dynamics, and guide forest management. A proposal from the European Commission for a new forest monitoring framework at the European level aims in this direction but lacks the integration of some crucial and readily available resources and infrastructures. For this reason, the proposal risks to be a missed opportunity rather than a step forward. Here we provide suggestions to help reconciling the proposal with its objectives and a more comprehensive monitoring vision.

The ability of world's forest to provide their services and contribute to achieving climate targets is increasingly threatened by global changes (Burgess et al., 2022; Korosuo et al., 2023; Senf et al., 2021; van der Woude et al., 2023). New information requirements place challenges on forest inventorying and monitoring systems: they need to develop and become timelier and more comprehensive and expand beyond their traditional objective of assessing status and changes to better contribute to a more complete understanding of forest functioning (Futter et al., 2023; Gessler et al., 2022; Zweifel et al., 2023). Such a development is essential to better model forest dynamics, identify future scenarios of ecosystem functioning, guide management, and inform policy makers. Here, advanced inventory and monitoring programs with an augmented portfolio of attributes and fully integrated field measurements combined with proximal and remote sensing components can offer considerable advantages (Ferretti et al., 2024b).

Recently, the European Commission recognized these needs and proposed a framework regulation for a coordinated European Union (EU) forest monitoring (European Commission, 2023a, hereafter

* Corresponding author.
E-mail address: marco.ferretti@wsl.ch (M. Ferretti).

https://doi.org/10.1016/j.foreco.2024.121875
Received 29 February 2024; Received in revised form 27 March 2024; Accepted 28 March 2024
Available online 6 April 2024

referred to as "the proposal"). It is based on the EU Forest Strategy 2030 (European Commission, 2021) and has been developed through a public consultation process, expert and scientific workshops (European Commission, 2023b). The proposal aims to: (i) ensure coherent high-quality monitoring to track progress towards achieving EU targets, policy objectives and targets that concern forests including biodiversity, climate, and crisis response; (ii) improve risk assessment and preparedness; and (iii) support evidence-based decision-making by land managers and public authorities, and promote research and innovation. It intends to secure consistent monitoring at the EU level: it is justified by the transboundary nature of forest-dependant markets and climate change related risks, and lays down rules for the collection and provision of information to support EU legislation for enhancing forest resilience and multifunctionality. The envisioned forest monitoring system is based on (i) standardised forest data from aerial or space-borne ortho-imagery by Copernicus satellites or other equivalent systems centrally provided by the EC, and (ii) harmonized *in situ* data through a network of monitoring sites (National Forest Inventories – NFIs – or other networks) representative of the Member States' forest area, provided by them. An additional set of data (Proposal, Annex III) is also foreseen.

With its 227.4 $\times 10^6$ ha (34.8% of land area), forests represent an immense resource in Europe (Forest Europe, 2020) and the intention to promote their consistent monitoring is therefore very much welcome. Yet, the proposal already raised several criticisms and concerns (Ferretti, 2024; Eustafor, 2023). Here, moving from consideration about the proposal's premises, required data, data quality, and the proposal's overall concept, we attempt to provide suggestions to move forward, eventually help reconciling the proposal with its intended objectives and a more comprehensive monitoring vision. While we explicitly quote parts of the proposal, it is worth mentioning that it goes beyond the scope of this paper to suggest modification in the proposal's wording. Rather, we want to point at parts that – in our view – are exemplary of lack of comprehensive vision and should be carefully addressed when evaluating or revising the proposal. Further, and in order to better delineate the field of concern of this paper, we have deliberately not considered the implications that may originate from the parallel and independent development of the EU Soil Monitoring Law (Soil health - European Commission (europa.eu). Soil is an essential part of the forest ecosystem and is key for forest resilience: not connecting the two regulation initiatives may generate a potentially critical decoupling in monitoring, an issue that deserves a much closer look.

1. Premises

The proposal largely builds on the premise that "*no comprehensive system currently exists at the Union level that can ensure availability of comparable quality data across all relevant policy areas, including forest resilience and biodiversity*» (p. 17, bullet 7). Such an idea is reiterated in several parts, where the principles of subsidiarity and proportionality are advocated. Forest monitoring is considered "*patchy and fragmented…*" with Member States "*acting alone in an uncoordinated manner over many years*" (p. 5). In particular, "*While…forest ecosystems often stretch across boundaries, … no consistent, transnational data-gathering approach has been fully developed so far*" (p. 5). The aforementioned statements, however, conflict with reality. While there are several internationally co-ordinated infrastructures and program dealing with the long-term observation of forest ecosystems (e.g. Futter et al., 2023), the most striking example is probably the monitoring scheme originating in large parts from the EC itself. In 1986, the EC prompted EU Member States to start a co-financed, coordinated forest monitoring scheme (EEC, 1986; Vel, 1996) that has evolved in close co-operation with the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) under the auspices of United Nations Economic Commission for Europe Air Convention (Sanders et al., 2016). Today, the monitoring originated in 1986 is still running, though no longer supported by the EC but by the participating Countries, as a harmonized international activity under the co-ordination of the ICP Forests. Contrary to what is stated in the proposal's Impact Assessment (European Commission, 2023b), the forest monitoring under the ICP Forests is not only internationally co-ordinated, but also covers the large majority of European countries (Fig. 1).

Originally concentrated on air pollution effects and forest damage, the monitoring evolved over the past 40 years to cover all forest ecosystem compartments, encompassing atmosphere, biosphere, geosphere and hydrosphere. A comprehensive set of harmonized and continuously reviewed methods (ICP Forests, 2022; Ferretti and Fischer, 2013), several of them published between 1986 and 1997 by the EC in its Official Journal (Cenni and Ferretti, 1998; see also Fig. 1) has been developed and applied. Formal Quality Assurance/Quality Control procedures, a centralized database with more than a thousand data checking routines, a structured governance system, and a formal data policy were developed over the years (ICP Forests, 2022). This effort generates data not only for international reporting (e.g. Forest Europe, 2020) and other EC Directives (e.g. National Emission Ceilings Directive, NECD[1]) but also for scientific advances in several fields directly related to forest resilience, vitality, growth, and carbon sequestration (De Vries et al., 2006; Etzold et al., 2020; Neumann et al., 2017; Jaime et al., 2022; Anthony et al., 2022; 2024), biodiversity (van der Linde et al., 2018; Weldon et al., 2022; Dirnböck et al., 2014; Vos et al., 2015), air pollution and forest ecosystem biogeochemistry (Camino-Serrano et al., 2016; Ferretti et al., 2024a; Guerrieri et al., 2024; Jonard et al., 2015; Verstraeten et al., 2023; Wohlgemuth et al., 2021), economic losses (e.g. Hanewinkel et al., 2013), and model calibration and evaluation (Reyer et al., 2014; Wergifosse et al., 2022).

With this background not only the aforementioned statements seem poorly substantiated but also the declared intention to "*minimise the extent to which Member States will have to adapt their data acquisition methods"* (proposal, p.5) appears elusive as the proposal *de facto* ignores substantial structures and assets already in place in individual Countries. These structures include national co-ordination centres, networks of monitoring plots (see Fig. 1), expertise in several monitoring fields, manuals of harmonized methods covering all forest ecosystem compartments (ICP Forests, 2022), data control routines, and uniform data reporting formats and procedures.

2. Required data

The proposal has its main focus on carbon sequestration as well as on data requirements and is largely concerned with trees and timber resources. Little is foreseen in relation to e.g., forest health and vitality, a key aspect when considering forest resilience (e.g. Senf et al., 2021; Jaime et al., 2022; Sousa-Silva et al., 2018). Forest health depends on a suite of biotic and abiotic factors (e.g. Sinclair, 1965; Manion, 1981; Trumbore et al., 2015) that are important to monitor and can be expressed by multiple metrics. Nevertheless, the proposal mentions only "defoliation" defined as reduced Leaf Area Index (LAI) based on the Copernicus data with a biweekly and 300 m resolution. While the assessment of LAI via remote sensing is still subject to several constrains (e.g. Brown et al., 2020), it remains questionable whether reduced LAI - which may depend on a variety of reasons, including phenology (Brown et al. 2017) and adaptive processes (Meier and Leuschner, 2008) - is an adequate measure of defoliation and especially of forest health, for which a much closer look is necessary. Further, the resolution of 300 m raise doubt to capture forest stand, yet alone, tree dynamics. It is therefore critical to define how remotely sensed LAI data will be validated, calibrated, and ground-truthed. Here it is worth noting that, for example, data on defoliation are not routinely collected by the NFIs, i.e., the only ground-based monitoring systems explicitly mentioned in the

[1] Directive - 2016/2284 - EN - EUR-Lex (europa.eu)

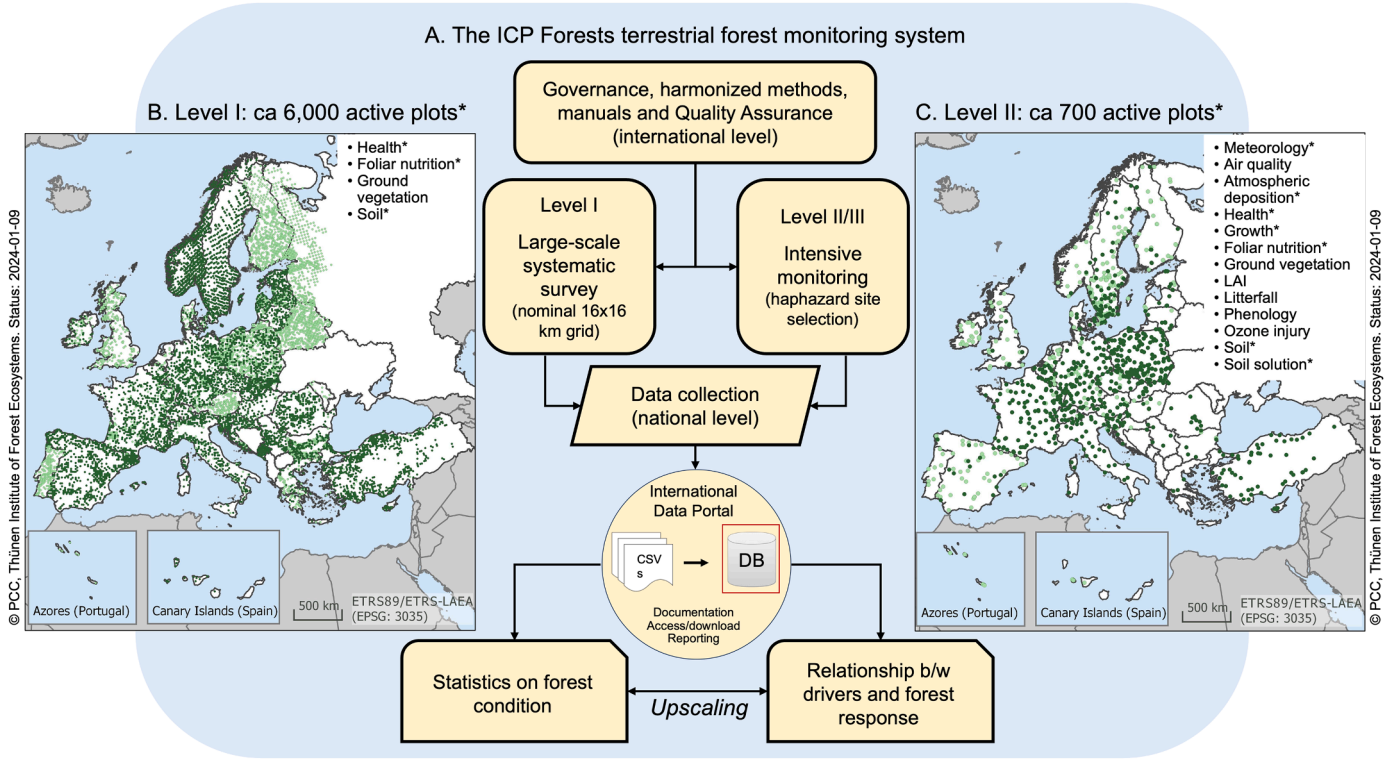

Fig. 1. The ICP Forests pan-European monitoring system. The concept (A) is based on two differentiated monitoring levels, with two networks (B: Level I; C. Level II; dark green: active plots in 2022; light green: currently non-active plots) installed by participating Countries (partly with the co-financing of the European Commission). The system functions according to internationally harmonized methodologies for both Level I and II (see list of harmonized methods within each map) and nationally co-ordinated data collection. Asterisks identify networks/surveys/methodologies for which provisions have been published in the Official Journal of the European Union. All methodologies are available under http://icp-forests.net/page/icp-forests-manual. Field data are validated at national and later at central level, used for reporting, and available upon request.

proposal so far. On the contrary, defoliation is the key attribute for ICP Forests (Bussotti et al., 2024; Michel et al., 2023; Potočić et al., 2021) and it is assessed on an annual basis on both Level I and Level II networks (Fig. 1) since decades. We suggest that this can offer a substantial basis (ca. 7000 plots; >30-year time series) not only for assessing forest health in space and time, but also for ground truthing of remotely sensed LAI data. In this context, LAI data might rather be seen as a proxy to favor spatio-temporal modeling based on field observations than as a non-validated, stand-alone measurement.

Biodiversity is another focus of the proposal. Specific data are requested for tree species composition and richness, deadwood, and forest birds. Presence of invasive plant and tree species, diversity of non-tree vegetation, and threatened species are also mentioned but with few methodological details and subject to future monitoring development. It is again worth noting that important monitoring approaches regarding biodiversity (e.g., ground vegetation, epiphytic lichens – see results by Giordani et al., 2014; Seidling et al., 2014; Van Dobben and De Vries, 2017) have already been harmonized at international level, new ones (e.g. mycorrhiza) have been largely and successfully tested at the European scale (van der Linde et al., 2018; Anthony et al., 2022, 2024), and additional ones (e.g. metabarcoding for biodiversity in soil and water samples and in insect traps) uses the ICP Forests plot infrastructure for development and testing.

Overall, the requested data and the suggested data sources may enable an assessment of forest resources and its changes, but will have limited potential in quantifying forest condition and driver-response relationships as well as processes, which are a prerequisite for the development of adaptation and mitigation measures within the context of resilient forests (Ferretti et al., 2024b). It is therefore arguable whether the newly proposed monitoring can actually address the information needs related to climate change adaptation (proposal, p. 16, point 13) and resilience. In addition, the proposal suggests in several parts new income possibilities to actors of the forest sector by certification schemes based on the suggested monitoring. There is a risk, however, that the promotion of carbon removal activities without adequate monitoring of their consequences for e.g., forest health, biodiversity, and nutrient sustainability may be detrimental for sustainable and multifunctional European forestry.

3. Data quality

The proposal raises major concern also with respect to data quality. While data comparability, quality, and availability are considered strategic objectives, it is unclear how they will be achieved. As for data quality, apparently (Art. 10) everything is left to the Member States (though the EC retains the power to adopt and implement delegated acts). Data comparability may be less of an issue for the Earth Observation component but will certainly be one for ground-based field data, especially if data quality and comparability will be dealt with at the national level only. Here, “harmonization” and “harmonized data” are frequently mentioned but the way how this will be achieved is unclear. Data availability from NFIs, which is a basis of joint transnational quality control and data harmonisation also through the EU Copernicus program, might also not be guaranteed as the current debate on data access suggests (Gessler et al., 2024; Schadauer et al., 2024). Mechanisms according to which field data should be made available to the Commission while, for example, protecting plot co-ordinates (a key and controversial topic, e.g., Nabuurs et al., 2022; Päivinen et al., 2023) are mentioned in the proposal, but no methods are mapped out, and ongoing discussions (see Gessler et al., 2024; Schadauer et al., 2024) raise doubts that these issues can be solved easily.

In this respect, it is also stated that in the past “*there has been no work*

on harmonising other ground-based data on variables, especially relating to biodiversity" (p. 1). This is another statement that does not stand against the considerable multi-disciplinary harmonization activity already developed, for example, within the NFIs (Alberdi et al., 2016; Gschwantner et al., 2022; Vidal et al., 2008) and ICP Forests (Ferretti et al., 2009; Ferretti and Fischer, 2013; König et al., 2013) and which can be readily used.

4. Conceptual vision

The proposal claims to be based on the latest scientific evidence, but it is not clear in what respect this is to be intended. Certainly, combining remote sensing and ground-based data for obtaining quantitative information is definitely not a new suggestion (e.g. Schmid-Haas, 1985), and is already common practice in e.g., many NFIs (e.g. McRoberts and Tomppo, 2007) and – though less regularly – also within ICP Forests (e.g. Alekseev and Chernikhovskii, 2022). On the contrary, it is rather surprising that the proposal did not leverage the wealth of other forest monitoring systems that have been developed over the past 40 years, as this can hamper the degree to which the proposal can achieve its stated objectives. While the most relevant example is likely ICP Forests due to its harmonized, long-term, large-scale nature and multi-level design with a focus on forests, other international monitoring networks and research infrastructures such as the ICP Integrated Monitoring,[2] eLTER,[3] and ICOS[4] (e.g. Futter et al., 2023) should be considered in the context of resilient forests. With their large portfolio of measurements, these aforementioned networks would provide invaluable contributions especially when the "process understanding" part of the monitoring, an important missing component of this proposal, is considered. Ignoring the wealth of existing monitoring resources is not only surprising because it affects the ability of the proposal to achieve its stated objectives. It is surprising also when considering that the EU (i) had a key role in installing and financing existing systems, (ii) is a signatory member of the UNECE Air Convention, and (iii) invests in projects aiming at promoting future monitoring where different communities (including NFIs, ICP Forests and remote sensing) are already collaborating (e.g., HORIZON EUROPE PathFinder,[5] FORWARDS,[6] MoniFun[7]; COST Action CLEANFOREST[8]). Further, in the frame of other EU Directives (e.g., NECD), Member States are recommended to use existing ICP Forests plots and Manuals for their field observations (Landgrebe et al., 2022). Yet, while the new EC proposal refers also to "*other networks of monitoring sites*", a clear priority is given only to NFIs. This is a very narrow – perhaps obsolete – conceptual vision. Although NFIs are certainly key players, a single focus on NFIs is not in line with the preparatory consultations: for example, the summaries of the scientific workshops held to provide input to the proposal under the Czech and the Swedish Presidency of the Council of the EU clearly stated that they "*welcomed the results of previous efforts on harmonization and evaluation carried out by ENFIN,[9] ICP Forests, the scientific community and others*" and encouraged the EC to "*build on the available knowledge and create further synergies in collecting forest-related data and indicators*" (Czech Presidency, 2022). Also, it was observed that "*co-ordination with Forest Europe, FAO/FRA,[10] ENFIN and ICP Forests, as well as EUROSTAT; EEA,[11] CBD,[12] and UNFCCC[13] would secure consistency with …established international processes.*" (Swedish Presidency of the Council of the European Union, 2023).

5. How to move forward

As it was the case at the time of the "forest decline" in the 1980s, the recent concern for the condition of European forests prompted a renewed interest for effective international monitoring (Ferretti, 2021). Almost 40 years ago, faced with the challenge of another transboundary issue (air pollution), the EC Regulation 3528/86 aimed to "*establish, on the basis of common methods, a periodic inventory of damage caused to forests…; — establish or extend, in a coordinated and harmonious way, the network of observation plots required to draw up that inventory*". Back then, the idea to install such a Europe-wide monitoring system was visionary and prompted an unprecedent co-ordinated monitoring effort by Member States (and beyond, as cascade effect). Today, it seems therefore obsolete that the EC proposal for a new monitoring framework for resilient forests ignores the co-ordinated monitoring infrastructures that Member States have since established across the Union.

Having in mind that the proposal is still under discussion, and that concerns have been already repeatedly expressed (e.g. Eustafor, 2023; Ferretti, 2024) we therefore suggest a few steps to reconcile the proposal with a more comprehensive monitoring vision and its stated objectives:

(i) revising, further developing, and updating the suggested monitoring concept by leveraging the existing and available internationally co-ordinated monitoring networks. In our view, the concept should identify, include and explicitly mention those networks that – together with NFIs – can contribute in achieving the stated objective of the proposal (see above) and at the same time alleviate the burden for Member States. Contributing network should have the necessary requirements in terms of:

- Ability to provide the data necessary to address the various issues related to resilience. Here, the ability to provide ground-based thorough descriptions and quantifications of forest health is essential. This can be achieved by identifying and quantifying the actual health status and the causes of damage at tree level.
- Achieved level of international harmonization and/or standardization. The extent at which European-scale harmonized and/or standardized methodologies exist for the different variables of interest.
- Documented data quality. The extent at which data quality is ensured at international level to achieve agreed and formally defined data quality objectives and favour data comparability across Europe.
- Potential for ground truthing. The extent at which a certain network is able to provide data for ground-truthing of remotely sensed data, e.g. defoliation. It involves the availability of the data for the variable of concern and the necessary plot size.
- Clear data access rules. Unambiguous and fair access rules to the data through clear Intellectual Property and unbiased sharing principles.

Examples of potential candidates networks have been mentioned in the previous chapters. Clear identification of contributing networks will have two important consequences: it will promote "coherent high-quality and consistent monitoring" across Europe (which is one of the objective of the proposal) and, by clarifying their expected input in terms of data and in relation to the proposal's objectives, will permit to identify complementarities and synergies (see below).

[2] https://unece.org/integrated-monitoring
[3] Integrated European Long-Term Ecosystem, critical zone and socio-ecological (eLTER - Home (elter-ri.eu) (acces date: 11/01/2024)
[4] Integrated Carbon Observation System (ICOS - Integrated Carbon Observation System (icos-cp.eu) (acces date: 11/01/2024)
[5] https://pathfinder-heu.eu/ (access date 10/01/2024)
[6] https://forwards-project.eu/ (access date 10/01/2024)
[7] MoniFun (acces date 23/02/2024)
[8] https://cleanforest.eu/ (access date 10/01/2024)
[9] European National Forest Inventory Network (access date 10/01/2024)
[10] Food and Agriculture Organization of the UN/Global Forest Resources Assessments
[11] European Environment Agency
[12] Convention on Biological Diversity
[13] United Nations Framework Convention on Climate Change

(i) Identifying and exploiting complementarities and synergies between existing and available internationally co-ordinated monitoring networks, filling gaps when necessary (see also Bontemps et al., 2021). Existing inventorying and monitoring resources have different characteristics that can offer the basis for a collaborative approach. A typical example in this respect is represented by the comparison between NFIs and ICP Forests: NFIs have their strength in the sampling density/spatial coverage and statistical design, while ICP Forests is stronger in temporal resolution and range of attributes measured; NFIs have – by definition – a national focus, while ICP Forests was born international. A collaborative approach where both (and other) networks are considered and a defined set of common variables is agreed for both can boost the potential for continental-scale monitoring. Approaches and benefits on how to integrate data and information from both have been already studied (e.g. Massey et al., 2021) also in relation to defoliation (Travaglini et al., 2013). In turn, identification of complementarities and synergies will be pivotal for the next step (see below).

(ii) Developing an institutional framework for a collaborative multi-level, multi-tier integrated ground-based and remote sensing forest monitoring system. In the context of scarce financial and personal resource availability and a forest sector under stress as a result of augmented disturbances and unstable market condition, a feasible and sustainable way ahead would be to create conditions and incentives facilitating the cooperation among existing monitoring networks. This, however, will not happen spontaneously. Networks like e.g. the NFIs, the ICP Forests and others exist since decades and, despite some sporadic and/or national initiatives, little – if anything – has been actually done to favour and motivate a dialogue between them. Expanding the monitoring concept of the proposal towards a broader collaborative approach (see above) should consider creating an institutional co-operation forum where the collaboration can actually take place. There, collaboration rules, pathways and governance can be agreed upon and formalized. This will strengthen the role of the EU and other international institutions like the UNECE and – probably – will result into an easier implementation of the monitoring.

These steps seem necessary for a full use of existing resources – particularly important at a time of financial constrains for many Countries – and to join forces for accurate quantification of forest resources and their condition (e.g. Bontemps et al., 2021; Ferretti, 2024). Only building on a broad basis, from the existing ground-based monitoring and inventory schemes combined with the European Earth Observation systems, a timely detection of changes and damaging events affecting ecosystem services and a better understanding of forest ecosystem processes and dynamics will be possible.

At a time of accelerated changes induced by climate change, air pollution, invasive alien pests and diseases, we need to use all our knowledge to build resilience for our forests. It would be a missed opportunity if the future European forest monitoring system were not to take advantage of all its available resources.

CRediT authorship contribution statement

Marco Ferretti: Writing – original draft, Conceptualization, Writing – review & editing, Supervision. **Arthur Gessler:** Writing – review & editing, Conceptualization, Writing – original draft. **Nathalie Cools:** Writing – review & editing. **Stefan Fleck:** Writing – review & editing. **Rossella Guerrieri:** Writing – review & editing. **Tamara Jakovljević:** Writing – review & editing. **Manuel Nicolas:** Writing – review & editing. **Tiina M Nieminen:** Writing – review & editing. **Diana Pitar:** Writing – review & editing. **Nenad Potočić:** Writing – review & editing. **Stephan Raspe:** Writing – review & editing. **Marcus Schaub:** Writing – review & editing. **Kai Schwärzel:** Writing – review & editing. **Volkmar Timmermann:** Writing – review & editing. **Monika Vejpustková:** Writing – review & editing. **Lars Vesterdal:** Writing – review & editing. **Petteri Vanninen:** Writing – review & editing. **Peter Waldner:** Writing – review & editing. **Lothar Zimmermann:** Writing – review & editing. **Tanja Gisela Marion Sanders:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors are involved in the ICP Forests and – with the exception of AG, RG and PV – are all members of the Programme Coordinating Group (PCG) of ICP Forests at the time of writing this manuscript.

Data Availability

No data was used for the research described in the article.

References

Alberdi, I., Michalak, R., Fischer, C., et al., 2016. Towards harmonized assessment of European forest availability for wood supply in Europe. . Policy Econ. 70, 20–29. https://doi.org/10.1016/j.forpol.2016.05.014.

Alekseev, A.S., Chernikhovskii, D.M., 2022. Assessment of the state of forests based on joint statistical processing of sentinel-2B remote sensing data and the data from network of ground-based ICP-forests sample plots. Open J. Ecol. 12 (8), 513–528.

Anthony, M.A., Crowther, T.W., van der Linde, S., et al., 2022. Forest tree growth is linked to mycorrhizal fungal composition and function across Europe. ISME J. 16 (5), 1327–1336.

Anthony, M.A., Tedersoo, L., De Vos, B., et al., 2024. Fungal community composition predicts forest carbon storage at a continental scale. Nat. Commun. 15, 2385. https://doi.org/10.1038/s41467-024-46792-w.

Bontemps, J.D., Bouriaud, O., Vega, C., Bouriaud, L., 2021. Offering the appetite for the monitoring of European forests a diversified diet. Ann. For. Sci. 79 (1), 19.

Brown, L.A., Dash, J., Ogutu, B.O., Richardson, A.D., 2017. On the relationship between continuous measures of canopy greenness derived using near-surface remote sensing and satellite-derived vegetation products. Agric. For. Meteorol. 247, 280–292.

Brown, L.A., Meier, C., Morris, H., Pastor-Guzman, J., et al., 2020. Evaluation of global leaf area index and fraction of absorbed photosynthetically active radiation products over North America using Copernicus Ground Based Observations for Validation data. Remote Sens. Environ. 247, 111935.

Burgess, T.I., Oliva, J., Sapsford, S.J., Sakalidis, M.L., et al., 2022. Anthropogenic disturbances and the emergence of native diseases: a threat to forest health. Curr. For. Rep. 8 (2), 111–123.

Bussotti, F., Potočić, N., Timmermann, V., et al., 2024. Tree crown defoliation in forest monitoring: concepts, findings, and new perspectives for a physiological approach in the face of climate change. Forestry 97 (2), 194–212. https://doi.org/10.1093/forestry/cpad066.

Camino-Serrano, M., Graf Pannatier, E., Vicca, S., et al., 2016. Trends in soil solution dissolved organic carbon (DOC) concentrations across European forests. Biogeosciences 13 (19), 5567–5585.

Cenni E., Ferretti M. (1998). Protocolli e criteri adottati a livello internazionale. In: Ballarin-Denti A., Cocucci S M, Sartori F (Eds), Monitoraggio delle forest sotto stress ambientale, Fondazione Lombardia per l'Ambiente, Milano, Italy: 36-52. (Available under: Monitoraggio delle foreste sotto stress ambientale (flanet.org), accessed on 12.02.2024).

Czech Presidency. Summary of the workshop "Towards harmonized Forest Observation, Reporting and Data Collection framework", Kutná Hora, 14-16 September 2022. ⟨https://www.uhul.cz/wp-content/uploads/summary_of_workshop_26_9_2022.pdf⟩. Accessed on 26.02.2024.

de Vries, W.I., Reinds, G.J., Gundersen, P.E., Sterba, H., 2006. The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Glob. Change Biol. 12 (7), 1151–1173.

Dirnböck, T., Grandin, U., Bernhardt-Römermann, M., et al., 2014. Forest floor vegetation response to nitrogen deposition in Europe. Glob. Change Biol. 20 (2), 429–440.

EEC, 1986. Council Regulation (EEC) No 3528/86 of 17 November 1986 on the Protection of the Community's forests against atmospheric pollution. Off. J. Eur. Communities No L 326 (2), 2–4. ⟨https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:31986R3528⟩. of 21.11.1986.

Etzold, S., Ferretti, M., Reinds, G.J., et al., 2020. Nitrogen deposition is the most important environmental driver associated to continental-scale growth of pure, even-aged, managed European forests. For. Ecol. Manag. 458, 117762.

European Commission, 2021. New EU Forest Strategy for 2030. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. ⟨https://environment.ec.europa.eu/strategy/forest-strategy_en⟩ (access date 10/01/2024). European Commission, Brussels: 27 ps.

European Commission, 2023a. Proposal for a regulation of the European Parliament and of the Council on a monitoring framework for resilient European forests. Brussels,

22.11.2023, COM (2023) 728 final, 2023/0413 (COD): 25 ps. ⟨https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:728:FIN⟩.
European Commission, 2023b. Commission Staff Working Document Impact Assessment Report Accompanying the proposal for a Regulation of the European Parliament and of the Council on a monitoring framework for resilient European forests. Brussels, 22.11.2023 SWD(2023) 373 final, 2023/0413 (COD): 167 ps. ⟨https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023SC0373⟩.
Eustafor, 2023. Joint-statement_The-EU-sectors-role-in-ensuring-Sustainable-Forest-Management-and-conserving-biodiversity.pdf (eustafor.eu) (accessed on 23.02.2024).
Ferretti, M., 2021. New appetite for the monitoring of European forests (4 pp.). Ann. For. Sci. 78 (4), 94. https://doi.org/10.1007/s13595-021-01112-w.
Ferretti, M., 2024. Europe must join forces to monitor its forests. Nature 626, 954. https://doi.org/10.1038/d41586-024-00558-y.
Ferretti M., Fischer R. (Eds). Forest Monitoring. Elsevier Developments in Environmental Science 2013; 12: 507 ps.
Ferretti, M., Cailleret, M., Haeni, M., et al., 2024a. The fingerprint of tropospheric ozone on broadleaved forest vegetation in Europe. Ecol. Indic. 158, 111486.
Ferretti, M., Fischer, C., Gessler, A., et al., 2024b. Advancing forest inventorying and monitoring. Ann. For. Sci. 81 (1), 6.
Ferretti, M., König, N., Rautio, P., Sase, H., 2009. Quality assurance (QA) in international forest monitoring programmes: activity, problems and perspectives from East Asia and Europe. Ann. For. Sci. 66 (4), 1–12.
FOREST EUROPE. State of Europe's Forests. Publisher: Ministerial Conference on the Protection of Forests in Europe (2020). ⟨https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf⟩.
Futter, M.N., Dirnböck, T., Forsius, M., et al., 2023. Leveraging research infrastructure co-location to evaluate constraints on terrestrial carbon cycling in northern European forests. Ambio 52 (11), 1819–1831.
Gessler, A., Ferretti, M., Schaub, M., 2022. Forest monitoring to assess forest functioning under air pollution and climate change. Front. For. Glob. Change 137.
Gessler, A., Schaub, M., Bose, A., et al., 2024. Finding the balance between open access to forest data while safeguarding the integrity of National Forest Inventory-derived information. N. Phytol. https://doi.org/10.1111/nph.19466.
Giordani, P., Calatayud, V., Stofer, S., et al., 2014. Detecting the nitrogen critical loads on European forests by means of epiphytic lichens. A signal-to-noise evaluation. For. Ecol. Manag. 311, 29–40.
Gschwantner, T., Alberdi, I., Bauwens, S., et al., 2022. Growing stock monitoring by European National Forest Inventories: historical origins, current methods and harmonization. For. Ecol. Manag. 505, 119868 https://doi.org/10.1016/j.foreco.2021.119868.
Guerrieri, R., Cáliz, J., Mattana, S., et al., 2024. Substantial contribution of tree canopy nitrifiers to nitrogen fluxes in European forests. Nat. Geosci. 17, 130–136.
Hanewinkel, M., Cullmann, D.A., Schelhaas, M.-J., et al., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Change 3 (3), 203–207.
ICP Forests, 2022Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests http (2022) //icp-forests.net/page/icp-forests-manual (access date: 02.02.2024)ICP Forests – International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (..
Jaime, L., Batllori, E., Ferretti, M., Lloret, F., 2022. Climatic and stand drivers of forest resistance to recent bark beetle disturbance in European coniferous forests. Glob. Change Biol. 28 (8), 2830–2841.
Jonard, M., Fürst, A., Verstraeten, A., et al., 2015. Tree mineral nutrition is deteriorating in Europe. Glob. Change Biol. 21 (1), 418–430.
König N., Cools N., Derome K. et al. Data quality in laboratories: methods and results for soil, foliar, and water chemical analyses. In: Ferretti M, Fischer R (Eds). Forest Monitoring. Elsevier Developments in Environmental Science 2013; 12: 415–453.
Korosuo, A., Pilli, R., Abad Viñas, R., et al., 2023. The role of forests in the EU climate policy: are we on the right track? Carbon Balance Manag. 18 (1), 15.
Landgrebe R., Best A., Hayes F. et al. Guidance note on site selection 2022.
Manion, P.D., 1981. Tree disease concepts. Prentice-Hall, Inc.
Massey, A., Lanz, A., Ferretti, M., 2021. A design-based assessment of an expanded set of auxiliary sources for forest change estimation. Can. J. For. Res. 51, 1–12. https://doi.org/10.1139/cjfr-2020-0529.
McRoberts, R.E., Tomppo, E.O., 2007. Remote sensing support for national forest inventories. Remote Sens. Environ. 110 (4), 412–419.
Meier, I.C., Leuschner, C., 2008. Leaf size and leaf area index in Fagus sylvatica forests: competing effects of precipitation, temperature, and nitrogen availability. Ecosystems 11, 655–669.
Michel A., Kirchner T., Prescher A.-K., Schwärzel K. (Eds.). Forest Condition in Europe: The 2023 Assessment. ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). 2023; Eberswalde: Thünen Institute. https://doi.org/10.3220/ICPTR169780188100.
Nabuurs, G.-J., Harris, N., Sheil, D., et al., 2022. Glasgow forest declaration needs new modes of data ownership. Nat. Clim. Change 12 (5), 415–417.
Neumann, M., Mues, V., Moreno, A., et al., 2017. Climate variability drives recent tree mortality in Europe. Glob. Change Biol. 23 (11), 4788–4797.
Päivinen, R., Astrup, R., Birdsey, R.A., et al., 2023. Ensure forest-data integrity for climate change studies. Nat. Clim. Change 1–2.
Potočić N., Timmermann V., Ognjenović M. et al. Tree health is deteriorating in the European forests ICP Forests Brief No. 5 2021; Programme Co-ordinating Centre of ICP Forests, Thünen Institute of Forest Ecosystems. https://doi.org/10.3220/ICP1638780772000.
Reyer, C., Lasch-Born, P., Suckow, F., et al., 2014. Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. Ann. For. Sci. 71 (2), 211–225.
Sanders T., Michel A.K., Ferretti M. 30 years of monitoring the effects of long-range transboundary air pollution on forests in Europe and beyond, 2016.
Schadauer, K., Astrup, R., Breidenbach, J., et al., 2024. Access to exact National Forest Inventory plot locations must be carefully evaluated. N. Phytol. https://doi.org/10.1111/nph.19564.
Schmid-Haas P. Inventorying and monitoring endangered forests. IUFRO conference, August 19-24, 1985, Zurich, Switzerland. IUFRO Conference. Zurich, Switzerland. Eidgenössische Anstalt für das forstliche Versuchswesen, 1985; 405 ps.
Seidling, W., Travaglini, D., Meyer, P., et al., 2014. Dead wood and stand structure - relationships for forest plots across Europe. iForest - Biogeosci. For. 7, 269–281.
Senf, C., Sebald, J., Seidl, R., 2021. Increasing canopy mortality affects the future demographic structure of Europe's forests. One Earth 4 (5), 749–755.
Sinclair, W.A., 1965. Comparisons of recent declines of white ash, oaks, and sugar maple in northeastern woodlands. Cornell Plant 20, 62–67.
Sousa-Silva, R., Verheyen, K., Ponette, Q., et al., 2018. Tree diversity mitigates defoliation after a drought-induced tipping point. Glob. Change Biol. 24 (9), 4304–4315.
Swedish Presidency of the Council of the European Union, 2023). Towards harmonised forest monitoring and reporting for the EU – Swedish Presidency Summary from the workshop arranged on 1-2 February, 2023, Uppsala, Sweden. ⟨https://www.slu.se/contentassets/be60f1f069904d7094e8b2a296c1e364/presidency-summary-of-the-workshop.pdf⟩ (accessed on 26.02.2024).
Travaglini, D., Chirici, G., Bottalico, F., FERRETTI, M., Corona, P., Barbati, A., Fattorini, F., 2013. In: Ferretti, M., Fischer, R., editors (Eds.), Monitoring, 12. Elsevier, DENS, UK, pp. 105–136.
Trumbore, S., Brando, P., Hartmann, H., 2015. Forest health and global change. Science 349 (6250), 814–818.
van der Linde, S., Suz, L.M., Orme, C.D.L., Cox, F., Andreae, H., Asi, E., et al., 2018. Environment and host as large-scale controls of ectomycorrhizal fungi. Nature 558 (7709), 243–248.
van der Woude, A.M., Peters, W., Joetzjer, E., et al., 2023. Temperature extremes of 2022 reduced carbon uptake by forests in Europe. Nat. Commun. 14 (1), 6218.
van Dobben, H.F., de Vries, W., 2017. The contribution of nitrogen deposition to the eutrophication signal in understorey plant communities of European forests. Ecol. Evol. 7 (1), 214–227.
Vel, E., 1996. Protection of forests in the European Union against atmospheric pollution 1987-1996 (Eds). Green. Eur. 2 (96), 24.
Verstraeten A., Waldner P., Marchetto A. et al. Long-term trends in throughfall and total deposition of anthropogenic nitrogen and sulphur compounds in European forests 2023.
Vidal C., Lanz A., Tomppo E. et al. Establishing forest inventory reference definitions for forest and growing stock: a study towards common reporting 2008.
Vos, B. de, Cools, N., Ilvesniemi, H., 2015. Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey. Geoderma 251, 33–46.
Weldon, J., Merder, J., Ferretti, M., Grandin, U., 2022. Nitrogen deposition causes eutrophication in bryophyte communities in central and northern European forests. Ann. For. Sci. 79 (1), 24.
Wergifosse, de, L., André, F., Goosse, H., et al., 2022. Simulating tree growth response to climate change in structurally diverse oak and beech forests. Sci. Total Environ. 806, 150422.
Wohlgemuth, L., Rautio, P., Ahrends, B., et al., 2021. Physiological and climate controls on foliar mercury uptake by European tree species. Biogeosciences Discuss. 2021, 1–30.
Zweifel, R., Pappas, C., Peters, R.L., et al., 2023. Networking the forest infrastructure towards near real-time monitoring–a white paper. Sci. Total Environ. 872, 162167.