Bontemps et al. Annals of Forest Science (2022) 79:19
https://doi.org/10.1186/s13595-022-01139-7

INRAE

Annals of Forest Science

OPINION PAPER Open Access

Offering the appetite for the monitoring of European forests a diversified diet

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Abstract

Key message: Forest monitoring in Europe is turning matter of renewed political concern, and a possible role for *ICP Forests* health monitoring has been suggested to meet this goal (Ann For Sci 78:94, 2021). Multipurpose national forest inventory (NFI) surveys yet offer a sampling effort by two orders of magnitude greater than ICP level 1, have accomplished substantial methodological and harmonization progresses in the recent years, and therefore form a decisive contributor to future European forest monitoring incentives. Possible paths for the future development of a pan-European, comprehensive and more accurate monitoring are designed that stress a crucial need to build on the assets of the existing forest monitoring programs and favor their cooperation, in order to limit the co-existence of distinct forest monitoring processes.

Keywords: Forest monitoring, Forest inventory, European forests, ICP Forests, National forest inventory, Forest health, Forest resource, Integration

1 Background

Climate change increases the threats on forests, yet intended to play a key role in the climatic and sustainable development strategies of most European countries and of the European Union. This situation is renewing the interest for forest monitoring in Europe, as manifested in recent research calls of the EFI (2021) and EU *Horizon Europe* (namely, calls HORIZON-CL6-2022-CLIMATE-01-05 on a *European observatory of CC impacts*, and HORIZON-CL5-2021-D1-01-09, on the *Contribution of forest management to climate action*). In a recent opinion paper, Ferretti (2021) proposes that the *ICP Forests* health monitoring program (International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests, http://icp-forests.net) has a pivotal—if not leading—role to play in future forest monitoring in Europe.

From a policy perspective, the absence of a forest policy at the European level entails difficulties for attaining EU-wide objectives and actions (Wolfslehner et al. 2020), including the achievement of a commonly accepted and implemented forest reporting system. The new European Forest Strategy (European Commission 2021), built on the subsidiarity principle, has also emphasized the urgent need to improve forest monitoring to better capture the state of European forests, and support handling of the diversified challenges and priorities embraced in it, namely bioeconomy, forest biodiversity protection and restoration, maintenance of forest carbon stocks and sinks, and their interplay. In a chapter dedicated to forest monitoring, this strategy endorses a critical view on current monitoring infrastructures in Europe (Table 1), especially as regards the scattering and patchiness, frequency and resolution, or lack of coordination and comprehensiveness of current monitoring incentives.

In the analyses of both the EC (2021) and Ferretti (2021), the contribution of European National Forest Inventory surveys (NFI) and the substantial progresses

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Table 1 Criticisms and proposals formulated by the European Commission (2021) on current forest monitoring systems in Europe. Communication on the New European Forest Strategy for 2030 on July 16. 2021. Statements arise from the section Strategic forest monitoring, reporting and data collection

Criticism / proposal	Statement	Aspect of monitoring covered
Criticism 1 (C1)	Today the information concerning the status of forests in the EU, their social and economic value, as well as the pressures they face and ecosystem services they provide, is patchy There are several scattered monitoring and reporting mechanisms, but no strategic framework, which would bring these together and make it possible to comprehensively and jointly with Member States demonstrate that the EU is on the right track.	Split and integration of monitoring and reporting mechanisms
Criticism 2 (C2)	No comprehensive reporting requirements exist	Lack of clear and integrated monitoring objectives
Criticism 3 (C3)	There are challenges related to the use of remote sensing data together with ground-based data (i.e. lack of interoperability, common definitions, ambiguity in data interpretation, lack of long and comparable very high resolution time-series, limitations of the current standard forest products from Copernicus)	Challenge of remote sensing integration (definitions, precision, temporality) Limitations of Copernicus land monitoring
Proposal 1 (P1)	The Commission will put forward a legislative proposal for a Forest Observation, Reporting and Data Collection framework. This will establish an EU-wide integrated forest monitoring framework, using remote sensing technologies and geospatial data integrated with ground-based monitoring, which will improve the accuracy of monitoring	Legally binding EU agreement on monitoring, targeting spatial and objective integration with improved resolution
Proposal 2 (P2)	The focus should be on regular and more frequent cost-efficient reporting and update of data on priority EU policy-relevant topics, such as effects of climate change, biodiversity, health, damages, invasive alien species, forest management, and the biomass use for different socio-economic purposes. Monitoring has to be done with high spatial and temporal granularity. Timeliness is particularly important also due to the rapid unfolding of forest natural disturbances. The framework will benefit from the EU Space Programme components and should leverage Galileo and Copernicus services to improve these processes	Multipurpose monitoring to address forest multifunctionality Greater spatial precision and temporal frequency Common framework for remote sensing data
Proposal 3 (P3)	The Forest Information System for Europe (FISE) will be enhanced to become the corner stone for harmonised forest data in Europe. The integrated forest monitoring system will therefore be framed under and its results made available through this information system	FISE as a support infrastructure
Proposal 4 (P4)	A dashboard on key indicators will be produced and updated yearly for indicators, such as those from remote-sensing data, which are readily available. Taking into account the risks and rapidly changing situation in EU forests, forest disturbances and updated risk assessments will also be part of the yearly reports.	Yearly reporting on indicators, including disturbances

they have recently accomplished to meet the EFS objectives however seem largely overlooked. In this contribution, we therefore intend to demonstrate what features make NFI surveys a cornerstone of European forest monitoring, and how they may contribute to future monitoring incentives together with other existing monitoring frameworks.

Table 2 Occurrences of publications where *forest monitoring* appears in the title of academic publications

Period	Occurrences	Annual
1991–2000	279	**27.9**
2001–2005	176	**35.2**
2006–2010	307	**61.4**
2011–2015	517	**103.4**
2016–2021	495	**99.0**

Request on Google Scholar dated 13 January 2021

While the use of *monitoring* in the forest terminology is of increased frequency (Table 2), it however embraces multiple definitions, objectives and scales. Here, monitoring follows the definition of De Gruijter et al. (2006), which is the *collection of information on an object through repeated or continuous observation in order to determine changes in the object*. Monitoring is hence distinguished from a *survey* which is a *single observation of an object with spatial extent* (same reference). Yet, a temporal sequence of surveys for updating information is also termed monitoring. Hence, *status monitoring* as a *repeated quantitative description of one universe as it changes with time* and *trend monitoring* as a *temporal description of one universe to decide whether temporal trends are present in the universe* can be distinguished. A *universe* is defined itself as *a biotic or abiotic system varying in space and/or time,* and identified to a *population* to be sampled. It can be discrete or continuous, as is, e.g., *the natural vegetation in an area during a period*

(De Gruijter et al. 2006), of primary interest here. We refer to these definitions and distinctions in the following.

2 National forest inventories: also a major component of forest monitoring in Europe

ICP systematic network has been designed to monitor forests at the tree and site levels (ICP level 1, hereafter ICP1). Selected sites are also intensively monitored in ICP level 2. Both have a permanent status. ICP therefore belongs to *trend monitoring* systems. Critically, ICP1 does not encompass any area-based procedure to statistically infer population attributes over the forest area considered. Thus, ICP monitoring tends to assimilate the *universe* or *population* under scrutiny (De Gruijter et al. 2006) to the plot network being matter of a monitoring, rather than consider it as a random collection of sampling units, belonging to the whole forests and forest trees of Europe as genuine *populations*. In parallel, forest information relevant to forest resources, carbon and biodiversity and comprehensive over European forests, has largely stemmed from National Forest Inventory (or NFI) surveys up to now (Breidenbach et al. 2021). These programs have been progressively deployed and enforced throughout Europe since the early twentieth century, and up to very recently in Eastern Europe (Bontemps 2021; Supplemental Material), with a strategic view of documenting both the status and changes of forests and support forest and environmental policies (Tomppo et al. 2010). Forest inventories are therefore designed as repeated spatial surveys over time, and hence belong to *status monitoring* systems.

2.1 An extended and increasing collection of forest indicators

The collection of forest ecosystem-, biodiversity-, and environment-oriented indicators by NFI surveys has also largely increased over time (Tomppo et al. 2010, chapter 4; Breidenbach et al. 2021), along with growing awareness for environmental issues (*Forest Principles* of the Rio conference, UN 1992). With the development of new, dedicated indicators, the use of NFI data for the quantification of forest biodiversity has experienced a strong development in recent years (e.g., Rondeux and Sanchez 2010, Storch et al. 2018, Bertrand et al. 2011, Chirici et al. 2012). The monitoring of climate impacts on forests by means of forest inventories is also progressing (e.g., Taccoen et al. 2019 on mortality, Charru et al. 2017, Ols et al. 2020, 2021 on growth). NFI surveys are hence strongly multipurposed and collect tens to hundreds of indicators on forests, a logic fully integrated into—and supported by—their sampling and estimation framework. In a significant set of European countries, forest inventory and forest health monitoring (ICP1) surveys are further performed on the same sampling designs (Kovac et al. 2014, Travaglini et al. 2013 Table 7.2), ICP1 monitoring being conducted on systematic subsamples of NFI grid plots. Such an initiative also dates back to 20 years ago in the USA, where the Forest Health Monitoring program (FHM) has been integrated into the "enhanced" *Forest Inventory and Analysis* (FIA) program (Brad Smith 2002) since the 1998 Farm Bill. These incentives offer experience and lessons for achieving forest monitoring integration in other countries.

Since NFI contribute to official European (MCPFE/Forest Europe) and World (UN/FRA) reporting processes, the recent criticisms formulated in the EFS (Table 1) should therefore be primarily considered within the NFI approach framework. These have been partly scrutinized in a recent communication by ENFIN (the European National Forest Inventory Network association, ENFIN 2021), and are addressed in the following.

3 European harmonization in NFI surveys: achievements and gaps

The lack of European integration in NFI-based information (Table 1, criticism C1 across space) has been acknowledged for around 20 years now, and is at the very origin of a substantial pan-European harmonization effort, especially funded by the EU, and initiated by COST actions E43 (https://www.cost.eu/actions/E43/ ; Tomppo et al. 2010) and FP1001 (https://www.cost.eu/actions/FP1001/; Vidal et al. 2016), and concretized in the Horizon H2020 project Diabolo (http://diabolo-project.eu), as recalled in ENFIN (2021) communication. The main achievements of this (still) ongoing process concern the adoption of common forest definitions (e.g., forest area, Vidal et al. 2008, Ståhl et al. 2012, Vidal et al. 2016) and of key forest variables (e.g., forest growing stock, Gschwantner et al. 2022), suggesting that NFI programs are indeed *on the right track* (Table 1).

Yet, and while not discussed in ENFIN (2021), one major loser of harmonization approaches to date remains the inventory *design*, which encompasses all spatio-temporal features of the sampling and survey of forests. Whereas all NFIs rely on a spatially systematic design, spatial stratification and sampling intensity vary widely across countries (Gschwantner et al. 2022). Also, a variety of approaches have been implemented as regards the status of NFI surveys (either enforced as permanent by Law, or with funding renegotiated at regular occasions), their temporal frequency (10, 5 years, or even annual in a few countries) and that of statistics delivery. The same applies to field plot status—permanent, temporary or mixed—that has crucial influence on the monitoring perspective adopted, *trend* or *status* monitoring (De Gruijter et al. 2006). Plot status is not necessarily related to the survey status (e.g., NFI is enforced as permanent in France, but is based on temporary plots; Hervé 2016). Both sources of variation clearly contribute to patchiness or gaps of coordination in forest reporting. They also challenge the capacity of a spatially integrated and synchronized—and ultimately annual—monitoring, conflicted by the least common denominator of NFI survey frequency (Table 1, criticism C3). This weakness should however not hide the major cornerstones of these programs.

4 Monitoring the forests: systematicity, population inference, and resolution in NFI surveys

4.1 Systematicity and population inference on a European scale

A first salient asset of NFI surveys is their representativeness of forest territories, rooted in the spatially systematic sampling that they universally implement. This feature is not so universal in ICP1 monitoring, as participating countries can decide whether sampling is random, systematic, or tessellated (Ferretti et al. 2020), while ICP2 is more of a demonstrative network. Further, NFI surveys all implement a common statistical background that aims at population inference over the forest *universe*, or *population*. This area-based populational inference is able to describe cumulated quantities (e.g., total carbon stocks of the forests) or the magnitude of disturbances (e.g., fraction of the forest area showing forest decline) on spatially defined subdomains (e.g., in private forests, or in forests or south-western Europe), and more generally any parameter to be extracted from the population distributions of forest attributes and their intersections (e.g., in private forests of south-western Europe), mean and variance most essentially (De Gruijter et al. 2006). While this kind of information is crucial to European policies as embodied in the bioeconomy or the EFS strategies, this feature is not clearly identified in EC views on forest monitoring (Table 1, criticism C2). It is obviously not the target of a monitoring system like ICP1, where information has a primary significance at local plot scale, and therefore enables a more qualitative and causal (in the case of intensive plots of ICP2) monitoring of forests as well as it prioritizes *trend monitoring*. Gasparini et al. (2013) have hence demonstrated that the privileged site-monitoring orientation of ICP1 is not reactive with respect to large changes in Italian forests and in particular spatial forest extension, leading to biases in forest types and tree species coverage. Further, ICP2 shows a logical but worrisome trend to erosion in the spatial/temporal systematicity of the monitoring with target variables of increasing measurement cost or difficulty (e.g., crown condition measured annually on all 797 plots, tree growth/ground vegetation every 5 years on 769/723 plots, respectively, atmospheric deposition continuously on 545 plots, meteorology on 209 plots, http://icp-forests.net/page/level-ii). When targeting all forests of the European continent, the limits of country-based significance in NFI design (Section 2) are also underway to be compensated for. Since NFI rely on probabilistic samples, combining NFI samples from different countries is made possible by accounting for differences in the plot sample weights. Estimators developed to handle variable plot weights permit the estimation of, e.g., total growing stock, timber wood, or carbon sink in these forests and their associated sampling errors. Such estimators have been readily tested across European NFI surveys (Lanz 2012, Korhonen et al. 2014).

4.2 A spatial resolution and sampling intensity with no counterpart

A second asset is the spatial sampling intensity offered by these programs, whereby > 500,000 plots are regularly inventoried in the field across Europe, thus two orders of magnitude greater than that offered by ICP1 network (ca. 6000 plots, with a minimum theoretical constraint for plot number in participant countries being the forested area in km divided by 256—corresponding to a 16 x 16 km theoretical sampling network, Ferretti et al. 2020), a singular difference that may draw attention. While forest biodiversity monitoring is a priority of the European Forest Strategy (Table 1, proposal P2), Barbati et al. (2007, Table 4) have thus evidenced that 11 out of 76 European forest types (14.5 %) remain uncovered by ICP1 network at the European level, raising issues regarding the comprehensiveness of biodiversity monitoring obtained with this network. The current typical sampling intensity of NFI surveys is nevertheless deemed as insufficient to obtain precise estimates across all regionalized forest domains of a given country. In a context where precision is also a priority (Table 1, criticism C3), this has given room for testing and effectively implementing small-area inference technologies, based on the so-called *multi-source inventory* view (MS-NFI, Tomppo et al. 2008), whereby ground samples are statistically complemented by high-resolution auxiliary information to increase precision at a given field sampling effort. The innovation has been judged ground-breaking enough to deserve the Markus Wallenberg Price in 1997 (https://www.mwp.org/1997-erkki-tomppo). Serious concern can therefore be expressed about the precision that would be obtained by basing a European forest monitoring on sampling efforts and designs as encountered in current ICP1 network alone. Rather, a sample nesting strategy, where *ICP Forests* monitoring is conducted on a spatially systematic subsample of NFI sampling designs, has gained ground across Europe (Kovac et al.

2014, Travaglini et al. 2013) and would need a careful scrutiny.

4.3 The spatial adaptiveness of monitoring intensity across Europe

Also, in contrast to the rigidity of ICP1, spatial flexibility and adaptiveness of the sampling effort across space is permitted in three ways by NFI programs. First, the sampling grid of NFIs is regularly photo-interpretated in order to extend the ground sampling to newly forested zones, thus being comprehensive and updated. A mix of permanent and temporary plots is also often implemented, purposed to avoiding sample attrition and bias (Gasparini et al. 2013), in a context where European forests show strong pluri-decennial spatial extension (Bontemps 2021). Second, variations in the sampling design encountered across countries reflect implicit specific needs and forest contexts, actually constituting a primitive but direct form of spatial optimisation of the sampling effort. Third, most inventories rely on designs stratified spatially, with varying sampling intensity to account for regional forest specificities (e.g., Finland, Sweden, Germany, France, Romania; Tomppo et al. 2010).

5 Hybridizing ground monitoring and remote sensing information for both increased precision and temporal frequency

Remote sensing integration into ground monitoring systems forms a timely opportunity for their improvement, embedded in views of future forest monitoring in the EFS (European Commission 2021, Table 1, proposal P2), and also stressed by Ferretti (2021). NFI programs have strongly committed into integrating remote sensing information into their designs, in view of increasing the precision of forest estimations (e.g., Lister et al. 2020, Grafström et al. 2017 Kangas et al. 2018), giving rise to a large variety of approaches (Hawryło et al. 2020, McRoberts and Tomppo 2007) where populational inference remains a cornerstone.

A follow-up of this approach, initially intended for increasing spatial precision, may also permit to increase the temporal frequency of forest monitoring. While some NFI surveys operate systematic annual samples, output statistics are obtained by aggregating successive samples (e.g., successive 5-year laps in the Finnish NFI, 5-year moving window in the French, US or Swedish NFIs, same references and Fridman et al. 2014), with a loss of responsiveness. Annual samples indeed convey a restricted precision, not sufficient for comprehensive statistic delivery across countries. Therefore, they remain used for delivering statistics solely at country scale (van Deusen 2000, Breidenbach et al. 2020). By increasing the precision of statistics obtained from a single annual sample, the multisource approach may thus also enable genuine annual delivery of information, for these NFI programs based on systematic annual samples (Table 1, proposals P2 and P4). It should ideally be based on remote sensing information also renewed annually. Whereas some satellite products (e.g., *Sentinel*) offer this possibility, NFI surveys yet overwhelmingly resort to more resolved aerial imagery to date, placing a challenge on faster renewal of image acquisition. NFI surveys thus have a leading role to play in this hybridization approach of field plot and remote sensing data (Kangas et al. 2018), as advocated for in the EFS.

In this respect, a leading idea is not to reduce, but rather maintain or increase the size of ground-based samples. A dense field network is indeed crucial in the context of monitoring local resources or disturbances, even when multisource NFI is being used, as the number of field plots remains the limiting factor when developing and calibrating multisource models (Vega et al. 2021). Also, the performance of the approach depends on the correlations between field forest attributes and auxiliary data. These correlations remain weak for some attributes that remain mostly estimated from field information. Here again, the usability of a low-density network of plots such as ICP1 is questionable.

6 Diversity rather than selectiveness as a baseline for future forest monitoring: some scenarios

6.1 Trade-offs between ICP Forests and NFI surveys

We thus arrive at a point where ICP1 and NFI programs exhibit mutual trade-offs (Table 1, criticism C1). On the one hand, ICP indeed forms a worthy demonstration of the feasibility of pan-European monitoring integration, with *well-tested governance mechanisms* (Ferretti 2021) and, as stated by this author, *the greatest achievement of ICP Forests* [lies] *in its role in demonstrating the extent to which transnational forest monitoring is possible and feasible*. However, it remains focused on forest health monitoring, is of a limited sampling resolution, and does not deliver area-driven statistics on European forests. On the other hand, NFI surveys, despite their ongoing trans-national integration and harmonization, offer the requested methodological bases for producing monitoring information across wide forest territories, and are therefore most relevant to quantitative policy targets on current issues. They are strongly multipurposed in the indicators they deliver, and also support effective and promising developments in remote sensing integration. Yet, the absence of a strong coordination priority limits the pace of progresses, while environmental priorities call for reactivity.

6.2 Governance issues

The second difficulty arises from a rather tensed political context on these issues. The EC now prioritizes the adoption of a *common forest observation, reporting and data collection framework*, using remote sensing and ground-based monitoring, with a more frequent and cost-efficient reporting and high spatio-temporal granularity (European Commission 2021, Table 1, proposals P2 and P4). Resort to a legally binding EU regulation incentive has also been made explicit (proposal P1). The initiative has yet been strongly opposed by 11 leading forest country governments (*Letter of the Eleven* of July 5th 2021, Köstinger et al. 2021) in name of the EU subsidiary principle. This leaves limited chances for such approach to be implemented in a near future, especially if the existing competing forest policy processes and their reporting needs are considered (Lier et al. 2021, Edwards and Kleinschmit 2013). Advocation of this principle to thwart the European initiative nevertheless remains debatable, in the context of developing an integrated monitoring scheme at a European scale that, in essence, cannot be afforded by EU member states alone.

6.3 Options and paths for reaching an integrated European forest monitoring

In this uncertain context, options that would satisfy the *new appetite for monitoring* (Ferretti 2021) can be figured out. Three positioning criteria are here used for their design in view of current monitoring priorities, and intended to address the three criticisms formulated by the EC (Table 1). The ultimate goal may be to achieve a pan-European, multipurpose embracing forest health status, and more accurate forest monitoring. *Scale* (criterion 1)—forest monitoring systems have been designed both at country and European levels. Encompassing EU forests with a common framework is now desired not only to support European forest strategies and policies, but also and more generally to favor comparability across countries (Table 1, criticism C1 in its spatial dimension). *Integration* (criterion 2)—whereas both forest and forest health monitoring systems remain largely separated to date, noticeable examples of the fusion of their observational grids do exist (in the USA, Belgium, and countries scrutinized in Kovac et al. 2014 and Travaglini et al. 2013). Hybridizing those monitoring approaches is desired for an integrated forest monitoring (forest and health inventory, FHI), where, e.g., causes of health decline may be explored, and forest statistics could be conditioned on health status. By integration, we also mean that forest health monitoring endorses the critical statistical framework of forest inventory, for the sake of statistic delivery with a validity and significance across the forested area of Europe (Table 1, criticism C1 in its integrative dimension of indicators, and criticism C2). *Precision* (criterion 3)—forest health and forest monitoring differ in their sampling efforts by two orders of magnitude. Current NFI precision is further not sufficient to inform small forest territories. Increases in precision are thus desirable in both cases. They may be enforced through increasing the sampling effort, or more plausibly by resorting to remote sensing-based technologies (RS). High frequency of RS-acquisition should also help increasing the temporal frequency of monitoring (Section 4). Thus, and for the sake of simplicity, spatial and temporal aspects are not distinguished in this criterion (Table 1, criticism C3).

Based on these criteria, we suggest that distinct paths actually exist for achieving such a large goal. We do not mention partial paths where all three criteria would not be simultaneously met (e.g., Kangas et al. 2018 on RS technology inclusion, or Kovac et al. 2014 on forest resource and health monitoring integration) or where progress incentives largely operate at country scale.

6.3.1 Path 1—cross-country cooperation in NFI harmonization

Here, harmonization in European NFIs goes on based on trans-national cooperation (mainly the ENFIN group), including the implementation of statistical estimators applicable to hybrid samples constituted from national sampling designs. At this point, one is allowed to term such system a European Forest Inventory (EFI, criterion 1), where sampling designs remain largely national and unstandardized. In the continuity, the additional implementation of RS technologies may provide increased precision and a common approach may be agreed on (RS-EFI, criterion 3), based on developments, e. g., the nFIESTA approach (Adolt et al. 2019). Forest health protocols may also be systematically embedded in NFI protocols as done in some countries, at least for systematic subsamples (Kovac et al. 2014) to reach an RS-EFHI stage (criterion 2). At the crossroad of these two challenges, the remote sensing of forest disturbances may also assist NFI programs in allowing plot filtering or defining small-area domains of interest. Increased disturbance regimes may also renew the interest for alternative sampling designs like the disturbance-based design, as once formulated and tested in a pilot study of the Lake states in USA (van Deusen 2000). The two latter aspects may also be technologically supported by the EU (FISE, Table 1, proposal P3) and agreed with the *ICP Forests* community.

6.3.2 Path 2—EU enforcement of the subsidiarity principle

In this path, the EU initiates a legally binding agreement on an integrated forest monitoring framework in Europe (criterion 1). Here, *ICP Forests* may serve as a benchmark infrastructure and monitoring network starting point. A common protocol framework would renew both sampling and plot designs, and extend monitored indicators to a core of those usually tracked in NFI programs

(European Forest Monitoring, EFM, criterion 2). Increases in precision are solely obtained by RS-based technologies (criterion 3). In this trajectory, country NFI programs and improved EFM may coexist at different scales and resolutions, to meet both European and national priorities, without any necessary convergence. An ultimate alternative would be a full refoundation of European forest monitoring, which countries may also decide to nest within their own—also re-founded and more intensive—NFI surveys (historical example of Slovenia, Tomppo et al. 2010).

6.3.3 Path 3—co-existing inter-operable monitoring networks

This path would be followed if the political context does not favour forest monitoring integration, the subsidiarity principle being set aside. The *ICP Forests* initiative may be reinforced on a European scale, while countries keep on promoting their own NFI surveys. On the one hand, harmonization goes on across NFIs to reach the stage of RS-EFI (criterion 1 and 3). On the other hand, European health monitoring is also strengthened by RS-based approaches and leads to a form of RS-ICP (criterion 3). Thus, both major forest monitoring systems would be strengthened and would keep co-exist and overlap at two levels. Design-nesting or protocol harmonization for inter-operability may occur later or never (no achievement of criterion 2, except in some cases at country levels).

Obviously, the set of credible futures in forest monitoring remains diverse, as well as it offers several degrees of freedom. In view of the increasing climatic pressure, the target of forest resource and health monitoring integration appears to be the most critical. Thus, neither Ferretti proposal (2021) nor ENFIN inventory view (2021) alone may satisfy this *new appetite for forest monitoring*. But obviously some hybridization of both, in a way that satisfies both EU priorities and countries' sovereignty, with European forests' future as a priority. The need to clarify these options is urgent.

7 Conclusions

- The need for a reactive, precise, and comprehensive (including forest health indicators) pan-European forest monitoring is established and now matter of intense discussions.
- While NFI programs remain overlooked in this debate, their sampling intensity, their harmonization process, and the statistical and adaptive framework they have devised for elaborating population inference across wide areas should form substantial inputs for the design of future forest monitoring. New hybrid forest inventory methodologies show how remote sensing information can help make forest monitoring spatially and temporally more precise and reactive.
- *ICP Forests* monitoring program of forest health has demonstrated a cross-country integration capacity of significance. The integration of forest health monitoring into a more comprehensive monitoring framework further forms a priority.
- To date, different paths of progress of an integrated European forest monitoring can be devised that build on assets of the different existing monitoring systems. Thus, hybridisation of associated systems and concepts cannot be avoided.
- Clarification of these possible paths will largely depend on shared acceptance for EU interventionism on this issue, on cross-country cooperation, and also on clarifications on the long-term goals of a forest monitoring.

Code availability
Not applicable.

Authors' contributions
Conceptualization: Jean-Daniel Bontemps, Olivier Bouriaud. Writing—original draft preparation: Jean-Daniel Bontemps. Writing—review and editing: Olivier Bouriaud, Cédric Véga, Laura Bouriaud. All authors read and approved the final manuscript.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare that they have no competing interests.

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Received: 17 February 2022 Accepted: 25 March 2022
Published online: 11 April 2022

References

Adolt R, Fejfar J, Lanz A (2019) nFIESTA (new Forest Inventory ESTimation and Analysis): Estimation methods. Technical report, Diabolo project granted by European Union's Horizon 2020 programme, p. 27. https://cordis.europa.eu/project/id/633464/results/ Accessed 7 Apr 2022

Barbati A, Corona P, Marchetti M (2007) A forest typology for monitoring sustainable forest management: the case of European Forest Types. Plant Biosyst 141(1):93–103. https://doi.org/10.1080/11263500601153842

Bertrand R, Lenoir J, Piedallu C, Riofrío-Dillon G, de Ruffray P, Vidal C, Pierrat JC, Gégout JC (2011) Changes in plant species composition lag behing climate warming in lowland forests. Nature 479(7374):517–520. https://doi.org/10.1038/nature10548

Bontemps JD (2021) Inflation of wood resources in European forests: the footprints of a big-bang. Plos One:0259795; see. https://doi.org/10.1371/journal.pone.0259795

Brad Smith W (2002) Forest inventory and analysis: a national inventory and monitoring program. Env Poll 116:233–242. https://doi.org/10.1016/S0269-7491(01)00255-X
Breidenbach J, Grandhus A, Hylen G, Eriksen R, Astrup R (2020) A century of national forest inventory in Norway–informing past, present and future decisions. Forest Ecosyst 7:46
Breidenbach J, McRoberts RE, Alberdi I, Anton-Fernandez C, Tomppo E (2021) A century of national forest inventories–informing past, present and future decisions. Forest Ecosyst 8(1):36. https://doi.org/10.1186/s40663-021-00315-x
Charru M, Seynave I, Hervé J-C, Bertrand R, Bontemps J-D (2017) Recent growth changes in Western European forests are driven by climate warming and structured across tree species climatic habitats. Ann For Sci 74(2):33. https://doi.org/10.1007/s13595-017-0626-1
Chirici G, McRoberts RE, Winter S, Bertini R, Brändli U-B, Bastrup-Birk A, Rondeux J, Barsoum N, Marchetti M (2012) National Forest Inventory Contributions to Forest Biodiversity Monitoring. Forest Science 58(3):257–268. https://doi.org/10.5849/forsci.12-003
De Gruijter J, Bierkens MFP, Brus DJ, Knotters M (2006) Sampling for natural resource monitoring. Berlin - Heidelberg: Springer, p 332.
Edwards P, Kleinschmit D (2013) Towards a European forest policy—conflicting courses. Forest Policy Econ 33:87–93. https://doi.org/10.1016/j.forpol.2012.06.002
EFI (2021) New call for forest monitoring study. Grant G-01-2021, February 5th 2021. http://efi.int/news/new-call-forest-monitoring-study-2021-02-05 Accessed 7 Apr 2022.
ENFIN (2021) Toward a european forest monitoring system. Vienna, Austria, 2 pp. Last consulted in December 2021 on http://enfin.info
European Commission (2021) New EU Forest Strategy for 2030. Brüssels, 16 July 2021, COM/2021/572 final, p 27
Ferretti M, Fischer R, Mues V, Granke O, Lorenz M, Seidling W, Nicolas M (2020) Part II: Basic design principles for the ICP Forests Monitoring Networks. Version 2020-2. In: UNECE ICP Forests Programme Co-ordinating Centre (ed.): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, 33 p + Annex. http://icp-forests.net/page/icp-forests-manual. Accessed 7 Apr 2022
Ferretti M (2021) New appetite for the monitoring of European forests. Ann For Sci 78(4):94. https://doi.org/10.1007/s13595-021-01112-w
Fridman J, Holm S, Nilsson M, Nilsson P, Ringvall AH, Ståhl G (2014) Adapting National Forest Inventories to changing requirements – the case of the Swedish National ForestInventory at the turn of the 20th century. Silva Fennica 48:1095
Gasparini P, Di Cosmo L, Cenni E, Pompei E, Ferretti M (2013) Towards the harmonization between National Forest Inventory and Forest Condition Monitoring. Consistency of plot allocation and effect of tree selection methods on Sample statistics in Italy. Env Mon Assess 185(7):6155–6171. https://doi.org/10.1007/s10661-012-3014-1
Grafström A, Zhao X, Nylander M, Petersson H (2017) A new sampling strategy for forest inventories applied to the temporary clusters of the Swedish national forest inventory. Can J For Res 47(9):1161–1167. https://doi.org/10.1139/cjfr-2017-0095
Gschwantner T, Alberdi I, Bauwens S, Bender S, Borota D, Bosela M, Bouriaud O, Breidenbach J, Donis J, Fischer C, Gasparini P, Heffernan L, Hervé JC, Kolozs L, Korhonen KT, Koutsias N, Kovácsevics P, Kučera M, Kulbokas G, Kuliešis A, Lanz A, Lejeune P, Lind T, Marin G, Morneau F, Nord-Larsen T, Nunes L, Pantić D, Redmond J, Rego FC, Riedel T, Šebeň V, Sims A, Skudnik M, Tomter SM (2022) Growing stock monitoring by European National Forest Inventories: Historical origins, current methods and harmonisation. For Ecol Manage 505:119868. https://doi.org/10.1016/j.foreco.2021.119868
Hawryło P, Francini S, Chirici G, Giannetti F, Parkitna K, Krok G, Mitelsztedt K, Lisańczuk M, Stereńczak K, Ciesielski M, Wężyk P, Socha J (2020) The use of remotely sensed data and Polish NFI Plots for prediction of growing stock volume using different predictive methods. Remote Sens 12(20):3331. https://doi.org/10.3390/rs12203331
Hervé J-C (2016) France. Country Report. In Vidal et al. (eds) National forest inventories – assessment of wood availability and use. Springer, 385-404, https://doi.org/10.1007/978-3-319-44015-6_20
Kangas A, Astrup R, Breidenbach J, Fridman J, Gobakken T, Korhonen KT, Maltamo M, Nilsson M, Nord-Larsen T, Næsset E, Olsson H (2018) Remote sensing and forest inventories in Nordic countries—Roadmap for the future. Scand J For Res 33(4):397–412. https://doi.org/10.1080/02827581.2017.1416666
Korhonen KT, Riedel T, Lanz A (2014) Use of National Forest Inventories data to estimate biomass in the European Forests (SC13), Framework contract: Provision of forest data and services in support to the European Forest Data Centre. JRC, EC, Ispra, Italy
Köstinger E, Toman M, Mölder T, Leppä J, Denormandie J, Klöckner J, Siarka E, Nagy I, Vlčan S, Tánczos B, Gerhards K (2021) Joint Letter of Ministers responsible for Forestry of Austria, Czech Republic, Estonia, Finland, France, Germany, Hungary, Latvia, Poland, Romania and Slovakia on the EU Forest Strategy post-2020. Addressed to Franz Timmermans, executive VP of the EC. Vienna, Austria, July 5, 2021. Last consulted February 15, 2022. http://www.skog.no/wp-content/uploads/2021/07/Joint-Letter-on-EU-Forest-Strategy-post-2020.pdf
Kovac M, Bauer A, Stahl G (2014) Merging National Forest and National Forest Health Inventories to Obtain an Integrated Forest Resource Inventory – Experiences from Bavaria, Slovenia and Sweden. Plos One 9(6):e100157. https://doi.org/10.1371/journal.pone.0100157
McRoberts RE, Tomppo EO (2007) Remote sensing support for national forest inventories. Rem Sens of Env 110(4):412–419. https://doi.org/10.1016/j.rse.2006.09.034
Lanz A (2012) Estimators for the E-Forest Platform. 6 November 2012. In: Statistical calculations at European level using design-based estimators (SC8), Framework contract: Provision of forest data and services in support to the European Forest Data Centre (EFDAC). JRC, EC, Ispra, Italy
Lier M, Köhl M, Korhonen KT, Linser S, Prins K (2021) Forest relevant targets in EU policy instruments. Can progress be measured by the pan-European criteria and indicators for sustainable forest management? Forest Policy Econ 128:102481
Lister AJ, Andersen H, Frescino T, Gatziolis D, Healey S, Heath LS, Liknes GC, McRoberts R, Moisen GG, Nelson M, Riemann R, Schleeweis K, Schroeder TA, Westfall J, Wilson BT (2020) Use of Remote Sensing Data to Improve the Efficiency of National Forest Inventories: A Case Study from the United States National Forest Inventory. Forests 11(12):1364. https://doi.org/10.3390/f11121364
Ols C, Hervé J-C, Bontemps J-D (2020) Recent growth trends of conifers across Western Europe are controlled by thermal and water constraints and favored by forest heterogeneity. Sci Total Environ 742:140453. https://doi.org/10.1016/j.scitotenv.2020.140453
Ols C, Gschwantner T, Schadauer K, Bontemps J-D (2021) Unexpected negative effect of available water capacity detected on recent conifer forest growth trends across wide environmental gradients. Ecosystems. https://doi.org/10.1007/s10021-021-00663-3
Rondeux J, Sanchez C (2010) Review of indicators and field methods for monitoring biodiversity within national forest inventories. Core variable: Deadwood. Env Monit Assessment 164(1-4):617–630. https://doi.org/10.1007/s10661-009-0917-6
Ståhl G, Cienciala E, Chirici G, Lanz A, Vidal C, Winter S, McRoberts RE, Rondeux J, Schadauer K, Tomppo E (2012) Bridging National and Reference Definitions for Harmonizing Forest Statistics. Forest Sci 58(3):214–223. https://doi.org/10.5849/forsci.10-067
Storch F, Dormann CF, Bauhus J (2018) Quantifying forest structural diversity based on large-scale inventory data: a new approach to support biodiversity monitoring. Forest Ecosyst 5(1):1–14. https://doi.org/10.1186/s40663-018-0151-1
Taccoen A, Piedallu C, Seynave I, Perez V, Gégout-Petit A, Nageleisen L, Bontemps J-D, Gégout J-C (2019) Background mortality drivers of European tree species: climate change matters. Proc R Soc B. 286:20190386
Tomppo E, Haakana M, Katila M, Peräsaari J (2008) Multisource National Forest Inventory. Methods and Applications. Springer, Series Managing Forest Ecosystems, p 373
Tomppo E, Gschwantner T, Lawrence M, MCRoberts RE (2010) National forest inventories - pathways for common reporting. Springer, Heidelberg, Dordrecht, London, New-York. https://doi.org/10.1007/978-90-481-3233-1
Travaglini D, Chirici G, Bottalico F, Ferretti M, Corona P, Barbati A, Fattorini L (2013) Large-scale pan-European forest monitoring network: a statistical perspective for designing and combining country estimates. Example for Defoliation. Chapter 7. Dev in Env. Science 112(105):135
UN (1992) Non-legally binding authoritative statement of principles for a global consensus on the management, conservation and sustainable development of all types of forests. UNCED Conference, Rio, Brazil

Van Deusen PC (2000) Pros and cons of the interpenetrating panel design. In McRoberts R, Reams GA, Van Deusen PC Proceedings of the first annual inventory and analysis symposium, Report 212:14-19
Vega C, Renaud J-P, Sagar A, Bouriaud O (2021) A new small area estimation algorithm to balance between statistical precision and scale. Int J Appl Earth Obs Geo 97:102303. https://doi.org/10.1016/j.jag.2021.102303
Vidal C, Lanz A, Tomppo E, Schadauer K, Gschwantner T, di Cosmo L, Robert N (2008) Establishing forest inventory reference definitions for forest and growing stock: a study towards common reporting. Silva Fenn 42(2):247–266. https://doi.org/10.14214/sf.255
Vidal C, Alberdi I, Hernández L, Redmond J (2016) National forest inventories. Assessment of wood availability and use. Springer, Series Managing Forest Ecosystems, p 845. https://doi.org/10.1007/978-3-319-44015-6
Wolfslehner B, Pülzl H, Kleinschmit D, Aggestam F, Winkel G, Candel J, Eckerberg K, Feindt P, McDermott C, Secco L, Sotirov M, Lackner M, Roux J-L (2020) European forest governance post-2020. From Science to Policy 10. European Forest Institute:51. https://doi.org/10.36333/fs10

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