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Towards Near-Real-Time Forest Disturbance Monitoring in Europe: Expert Meeting and Stakeholder Consultation Report

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Abstract

Near-real-time (NRT) forest disturbance monitoring is increasingly relevant for European forest policy, carbon accounting, risk management, and operational forest management. In support of this agenda, the Joint Research Centre (JRC) convened an expert consultation process and an online expert workshop on 3 March 2026 to assess user requirements, review current technical capacities, and identify priorities for future European NRT forest disturbance monitoring. Drawing on 127 survey responses, ten semi-structured expert interviews, and expert discussions during the workshop, this report identifies substantial heterogeneity in user expectations across stakeholder groups and geographic contexts. Stakeholders expressed strong demand for timely disturbance information, high spatial detail, disturbance-type attribution, uncertainty information, and compatibility with existing institutional workflows. At the same time, the analysis highlights several operational mismatches between these expectations and current Earth observation capabilities, including irregular data availability caused by cloud cover, snow, terrain shadows, and seasonal limitations; constraints in achieving both high spatial resolution and low latency at continental scale; and the continuing difficulty of attributing observed canopy change to specific disturbance drivers.

To address these diverse requirements without assuming a single centralised operational solution, the report develops a vision for a collaborative, multi-tiered European forest monitoring ecosystem. In this framework, consistent pan-European baseline products would provide an institutional foundation for policy, reporting, and environmental oversight, while regional, national, and local systems would support more targeted, higher-resolution, and use-case-specific applications. Emerging artificial intelligence methods, including deep learning, foundation models, and natural-language interfaces, are discussed as potential accelerators for disturbance attribution, scalable time-series analysis, and improved accessibility of monitoring information. The report further outlines the JRC NRT Intercomparison Challenge, a standardised benchmarking exercise designed to evaluate the performance of diverse satellite-based forest disturbance monitoring workflows across 100 representative European sampling units. By providing an independent, scientifically defensible assessment framework, the initiative aims to support the development of robust remote sensing indicators for forest disturbance monitoring, carbon reporting, and ecosystem resilience in line with the objectives of the EU Forest Strategy for 2030.

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1. Introduction

European forests currently face an unprecedented combination of pressures, from climate change causing more frequent and intense natural disturbances to a greater human demand for wood and wood products (Senf et al., 2018; Grünig et al., 2026). In response, the European Commission, through its Forest Strategy for 2030 (COM 2021/572 final), has committed to developing advanced Earth Observation (EO) tools to systematically monitor these dynamics across the continent. Within this framework, the Joint Research Centre (JRC) plays a pivotal role through the European Forest Science Partnership. This initiative, alongside the ten-year European Partnership on Forests and Forestry for a Sustainable Future (European Commission, 2025), aims to defragment forest research and further develop the suite of remote sensing indicators used to ensure that robust scientific findings effectively reach both policymakers and local stakeholders.

Among these indicators, a critical focus is the monitoring of forest disturbances. Abrupt events such as windstorms, bark beetle outbreaks, and timber harvesting cause rapid localized modifications to the forest canopy (Coops et al., 2020; Brown et al., 2026). Understanding when and where these abrupt changes occur is vital, as they directly alter regional carbon budgets, disrupt local management timelines, and impact ecosystem resilience (Thorn et al., 2018; Gea-Izquierdo and Sánchez-González, 2022; Lecina-Diaz et al., 2024). Providing a regular, reliable overview of these canopy losses is therefore key to supporting European forest objectives and ensuring timely environmental oversight.

To address these needs, the focus of remote sensing workflows is shifting toward near-real-time (NRT) forest disturbance monitoring (FDM) by leveraging dense satellite time series from missions like Sentinel-1, Sentinel-2, and Landsat (Woodcock et al., 2020). However, the current European operational landscape remains fragmented. Most existing NRT systems were originally developed with a primary focus on tropical deforestation, and many European efforts remain confined to research environments, often not yet bridging the gap between proof-of-concept and full operationalization.

Furthermore, the perception of what constitutes "near-real-time" varies significantly across different user groups. For instance, the LULUCF (Land Use, Land-Use Change and Forestry) reporting community, which has traditionally relied on multi-year update cycles from National Forest Inventories, often perceives NRT as a shift toward annual or sub-annual outlier identification for carbon accounting. In contrast, operational forest managers may require actionable information within days to support salvage logging or pest containment efforts. Because harmonized disturbance monitoring addresses a critical gap in European-wide oversight beyond the established domain of forest fires, it stands as a major priority for both policy reporting and field management.

To address these challenges, the JRC organized a comprehensive expert consultation and a dedicated expert meeting on March 3, 2026. The initiative involved significant preparatory work by two external experts: one focused on the extensive analysis of stakeholder requirements across European user communities, while the other led the technical preparation and design of an intercomparison challenge to benchmark existing forest disturbances monitoring solutions for Europe. This collective effort culminated in a half-day online meeting that brought together approximately 50 academics and practitioners actively working on forest monitoring to discuss methodologies and operational needs. The broad objectives were to establish a clearer understanding of "fitness for purpose" regarding European stakeholder requirements, to review the current state of the art in algorithm development and operational lessons from systems like Global Forest Watch, and to launch a comprehensive intercomparison challenge.

2. On the definition of "Near-Real-Time"

The term "near-real-time" (NRT) has become a central concept in Earth Observation, but its operational meaning within the European forestry sector varies substantially across user communities and use cases. Conversation with both end users and algorithm developers indicated that the definition of NRT is not defined solely by absolute technical latency such as the number of hours or days between image acquisition and product delivery. Rather, its meaning depends on the extent to which available data streams can meet the temporal requirements of specific decision-making processes. For some users, NRT implies information delivered within days to support operational responses such as salvage logging, pest containment, or emergency assessment. For others, particularly those involved in reporting or strategic monitoring, annual or sub-annual updates may already represent a significant improvement over traditional multi-year inventory cycles.

2.1. The conceptual spectrum of NRT

Different user communities interpret NRT monitoring in relation to their specific operational mandates. For forest reporting and carbon accounting communities, the demand for NRT data often stems from the temporal limitations of traditional National Forest Inventories (NFIs). Since NFIs typically operate on multi-year cycles, they provide robust but inherently retrospective information. In this context, the term "near-real-time" is frequently used to describe a move toward increased update frequency; specifically, it represents a shift toward annual or sub-annual identification of breakpoints or abrupt trajectory changes. This allows the reporting community to capture significant shifts in forest dynamics within a single reporting period, rather than waiting for the multi-year lag of a traditional inventory cycle to register the impact of disturbances on carbon stocks.

In contrast, local authorities and operational forest managers define NRT primarily through the concept of actionable latency. For these stakeholders, monitoring is only "near-real-time" if it delivers information within a window that allows for active intervention, such as the containment of bark beetle outbreaks or the coordination of salvage logging following windthrow events. Here, the requirement is measured in days or weeks rather than months, highlighting that NRT is a relative term defined by the "shelf-life" of the information's utility.

Box 1. Note on terminology: Monitoring vs. Mapping

A useful distinction can be made between retrospective mapping and monitoring. Retrospective mapping focuses on characterising changes that have occurred over a defined period, usually prioritizing spatial accuracy, thematic detail, and consistency after the relevant observations have been collected. Operational monitoring, conversely, refers to the repeated or continuous observation of ongoing change, with emphasis on timely detection and rapid information delivery. While mapping may be sufficient for carbon accounting, historical analysis, and long-term reporting, monitoring is required when disturbance information is intended to support NRT operational response

2.2. Operational timeliness and algorithmic logic

From the perspective of an operational forest manager, the value of an NRT system is governed by its detection lag; the time elapsed between a physical disturbance and its digital confirmation. This lag is inextricably linked to the underlying algorithmic logic.

For carbon reporting needs, retrospective mapping algorithms are generally sufficient; these models can "look back" across a complete yearly time series to identify breakpoints with high confidence. However, such approaches are unsuitable for operational NRT needs because they often require "future" observations to confirm a past event.

For a system to serve an operational monitoring role, the algorithm must be capable of evaluating incoming satellite observations against a baseline as they arrive. Whether utilizing statistical modeling, adaptive filtering, or emerging spatio-temporal deep learning architectures, the detection logic must balance the need for speed with the risk of false positives. In an operational context, an NRT flag is only useful if the confirmation period is short enough to allow for a field response, yet robust enough to avoid the mobilization of resources based on ephemeral noise or atmospheric artifacts.

2.3. Environmental and technical constraints

Regardless of the algorithmic approach, the practical realization of NRT in Europe is subject to physical realities that dictate data availability:

- Atmospheric and Seasonal Interference: In persistent cloud-prone regions or high-latitude boreal forests, optical sensors may face gaps of several weeks. During winter, low sun angles, shadows, and snow cover further complicate the signal, effectively "pausing" NRT capabilities for a significant portion of the year in certain geographies.
- The Resolution-Latency Trade-off: There is often a technical tension between the desire for high spatial resolution (necessary to distinguish canopies of individual trees) and high temporal frequency. While radar provides an all-weather alternative, its sensitivity to surface moisture and freeze-thaw cycles requires sophisticated processing to avoid false positives, which can add to the total processing latency.

Ultimately, NRT is not a static technical specification but a relative performance metric. Recognizing that a system may be "near-real-time" for a policy report while being "delayed" for a forest ranger is essential for developing a framework that is truly fit-for-purpose across Europe’s diverse administrative and ecological landscapes.

3. A diversity of stakeholders with diverging requirements

Building a common understanding of user requirements is a fundamental prerequisite for any coordinated forest monitoring effort in Europe. Given the complexity of the European forest landscape; characterized by high fragmentation, diverse management regimes, and no single regulatory framework, the "fitness for purpose" of monitoring tools depends heavily on the specific mandate of the user. This section synthesizes the findings from the stakeholder consultation, including 127 survey responses and 10 semi-structured interviews (see Annex 1 and 2 for specifications and interview guides), and the subsequent validation of these results during the expert meeting.

3.1. Identification of key user communities

The consultation confirmed seven primary stakeholder groups, each with distinct operational realities. While EU agencies require pan-European consistency for high-level policy, local forest managers and private owners focus on the stand-level granularity necessary for daily management.

As shown in the initial assessment, requirements for spatial resolution and latency vary by orders of magnitude (Table 1). National authorities typically operate within 10–30 m resolution for LULUCF reporting, whereas forestry companies and local managers increasingly cite a need for sub-meter resolution and latencies of less than 48 hours to support rapid field interventions.

Table 1. Expert compiled overview over primary user and stakeholder groups as well as key characteristics and data needs

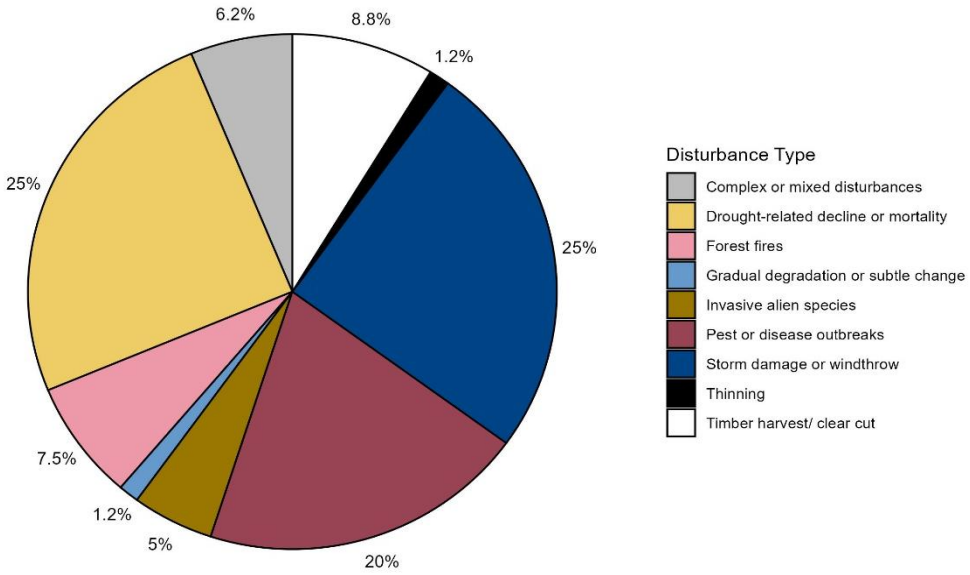
Stakeholder Group	Primary Role	What They Are Looking For	Main Data Types Used	Typical / Required Specs
National Forest Authorities & Environmental Agencies	Primary operational users; national monitoring and reporting	Early detection of storms, pests, drought dieback, fires, and large-scale harvests; spatially explicit alerts; consistency with national forest inventories; low false-positive rates	Sentinel-2 optical, Sentinel-1 SAR, Landsat, VHR optical (confirmation), LiDAR (structure/biomass, not NRT)	Current: 10 m, 5-6 day revisit, 2-7 day latency; Desired: ≤5 m, 1–3 day revisit, <48 h latency, SAR–optical fusion
Regional / Local Forest Managers & Protected Area Authorities	On-the-ground decision-making and management	Management-unit level alerts; disturbance type and severity; alignment with stands, compartments, Natura 2000 sites	Sentinel-2, Sentinel-1, UAVs (follow-up), VHR optical	Current: 10 m, 5–10 day revisit; Desired: ≤5 m, 2–3 day revisit, weekly or faster updates
EU Agencies & Copernicus Services (EEA, JRC, CLMS, EMS)	System-level coordination, pan-EU products	Pan-European consistency; comparable indicators; long-term time series; scalable and reproducible methods; uncertainty metrics	Sentinel-1/2 (core), Sentinel-3 (context), aggregated national inputs, EMS VHR	Current: 10–20 m, 5–6 day revisit, days–weeks latency; Desired: stable 3–5 day revisit, <3 day latency
Research Institutions & Method Developers	Development and validation of methods and indicators	Dense time series; multi-sensor data fusion; access to raw data and metadata; validation data	Sentinel-1/2/3, Landsat, hyperspectral (DESIS, PRISMA; future CHIME), LiDAR (GEDI, national), ERA5	Gaps: operational NRT hyperspectral, frequent LiDAR, labelled datasets for AI
Forestry Companies & Large Forest Owners	Operational and economic forest management	Very fast detection for salvage logging and pest containment; stand-level precision; integration with management systems	Sentinel-2 (screening), commercial VHR optical, commercial SAR, airborne LiDAR	Current: 0.5–3 m, daily possible, <24 h latency; Desired: guaranteed multi-weekly revisit, hours–1 day latency
Insurance, Risk & Carbon-Market Actors	Risk assessment, claims, MRV	Event detection and attribution; pre-/post-disturbance baselines; transparent and auditable methods; large-area coverage	Sentinel-1/2, VHR optical, SAR–LiDAR biomass proxies	Gaps: standardised NRT products; robust confidence/uncertainty estimates
NGOs & Environmental Oversight	Watchdog, compliance, advocacy	Rapid alerts of deforestation or degradation; communicable evidence; cross-border comparability	Sentinel-2, Landsat, VHR optical	Desired: alerts <1 week; clearer distinction between legal harvest and degradation

Source: JRC stakeholder consultation and requirement analysis

3.2. Geographic realities and the limitations of aggregate survey data

The survey results indicate that, at a continental scale, European priorities are overwhelmingly oriented toward climate-driven disturbances. Storm damage (windthrow) and drought-related decline were ranked as the most critical concerns, followed closely by pest and insect outbreaks.

Figure 1. Ranking of relevant disturbance types by stakeholder group.



Source: ETH Survey Data

However, during the expert meeting, these aggregated results were contextualized through the lens of regional variability. A notable observation from the roundtable discussion concerned the role of forest thinning. While thinning ranked very low in the broad stakeholder survey, participants from regions with intensive forest management (e.g., Finland) emphasized that thinning is much more common than natural disturbances in their specific contexts.

This example illustrates a broader reality: a monitoring indicator that is highly valued in one biome may be perceived as "noise" in another. It suggests that while a harmonized European approach is desirable, it must be flexible enough to accommodate different geographical priorities and management intensities.

3.3. The spatial and temporal resolution gap

The survey revealed a clear divergence between temporal and spatial expectations. While the temporal frequency requirements of the majority of stakeholders stabilized at standard sub-annual intervals, with weekly to monthly updates considered operationally sufficient, there was a surprisingly high demand for ultra-high spatial resolution.

- **Temporal**: Most users prioritized a latency of one week following a disturbance.
- **Spatial**: A majority of respondents requested data in the 16–50 cm (very high) or under 15 cm (ultra-high) range.

When these findings were presented at the expert meeting, they triggered a debate regarding "aspirational" versus "operational" needs. While domain experts are aware of the technical trade-offs inherent in satellite monitoring, the desire for tree-level detection (e.g., to identify early-stage "green attacks" by bark beetles or individual tree stress) likely remains a primary driver of these high expectations.

3.4. Insights from expert discourse: declared needs vs. practical utility

The presentation of the survey results during the meeting provided an opportunity to reflect on the potential divergence between declared preferences and actual operational uptake.

A critical point of reflection concerned the demand for uncertainty and confidence layers. While respondents consistently ranked uncertainty information as a high priority in the survey, experts noted a significant empirical gap regarding how such data is utilized in routine workflows. It was observed that outside of the forest fire monitoring community where the long-standing operational history of systems like EFFIS has allowed for some study of user behaviour (San-Miguel-Ayanz et al., 2012), there is very little documented evidence of how practitioners make use of data in their decision-making workflows.

There was consensus among the experts that while users often request these layers to ensure scientific or legal "defensibility," there is a risk that such information remains secondary to the "actionability" of an alert. In high-pressure operational environments, the simplicity and clarity of a detection signal may be more decisive for institutional uptake than the provided confidence metrics. This suggests that future efforts should focus not only on generating uncertainty data but also on understanding the interface through which it becomes useful to the end-user.

3.5. Operational prerequisites: reliability and integration

The consultation underscored that timeliness and spatial detail alone are insufficient. For monitoring information to be integrated into routine workflows, it must meet several non-technical criteria:

1. **Methodological consistency**: users, particularly in the insurance and reporting sectors, highlighted that discontinuities in products or changing definitions are significant barriers to institutional uptake.
2. **Actionable outputs**: there is a clear preference for interpreted information (e.g., disturbance classification) over raw detection signals.
3. **Flexible access**: rather than a single centralized platform, users expressed a preference for downloadable GIS-ready formats (GeoTIFF, Vector) that can be ingested into existing national or local systems.

In summary, the diversity of needs suggests that no single system can satisfy every requirement. The findings instead point toward a need for reliable, scientifically defensible information that can be adapted to the diverse institutional and ecological landscapes of Europe.

4. A vision for a multi-tiered European forest monitoring ecosystem

The expert consultation and subsequent roundtable discussions converged on a central realization: a "one-size-fits-all" monitoring solution (one that operates at ultra-high resolution with minimal latency and absolute reliability across all of Europe) is not only currently still technically unfeasible but perhaps conceptually misaligned with the diverse needs of the community. Instead, the findings point toward a vision of a multi-tiered monitoring ecosystem. This architecture balances the need for institutionalized, harmonized oversight with the agile, high-resolution requirements of local operational management.

4.1. Tier 1: The institutional foundation

The first tier would provide the institutional foundation of a European forest monitoring ecosystem: a robust, harmonised, and transparent set of pan-European monitoring layers. Rather than prioritising maximum temporal speed, this tier would emphasise methodological consistency, long-term continuity, reliability, and comparability across countries. Its main purpose would be to support policy development, LULUCF reporting, cross-border environmental assessment, and the establishment of a common evidence base for European forest condition and disturbance dynamics.

Elements of this institutional tier are already being implemented through the Copernicus Land Monitoring Service (CLMS) and its portfolio of High-Resolution Layers (HRLs). Further progress towards this vision is supported by initiatives such as the Horizon Europe projects EvoLand, FORWARDS, ForestNavigator or PathFinder which contributes to the development of next-generation Copernicus land-monitoring products. Enhancing the update frequency, temporal consistency and thematic resolution of these core products, would strengthen their role as a stable, wall-to-wall baseline for harmonised assessment of European forest dynamics.

4.2. Tier 2 and 3: Promoting bottom-up innovation

A reliable tier 1 layer can serve as an enabling foundation for more specialised, bottom-up monitoring approaches. By providing standardised and comparable baseline information, it allows regional, national, and local actors to build complementary services tailored to specific operational contexts.

- **The intermediate tier** could consist of specialised services or regional authorities that integrate tier 1 products with additional datasets, such as commercial SAR, very-high-resolution optical imagery, airborne data, or national reference information. This would support higher-frequency or higher-resolution alerts for specific biomes, disturbance types, or priority areas.
- **The operational tier** would support local decision-making by enabling forest managers to use these baseline layers as triggers for site-specific assessments. On-demand change-detection tools, for example, could allow users to analyse selected forest stands immediately after a local storm, suspected pest outbreak, or other observed anomaly. In this way, the operational tier would connect automated, broad-scale monitoring with targeted field response.

4.3. Synergy through a coordinated infrastructure

In this tiered vision, the meaning and implementation of NRT monitoring are defined at the level at which the information is intended to be used. The institutional tier would ensure that major

disturbance events are consistently recorded and can be incorporated into annual carbon budgets, policy reporting, and cross-border environmental assessments. Decentralized tiers, in contrast, would provide the granular spatial detail and shorter response times required for operational applications such as pest containment, salvage planning, or civil protection.

Conceptualising European forest monitoring as a coordinated information infrastructure rather than as a single centralised platform, distributes the requirements for performance, resolution, latency, and reliability across complementary system levels. The institutional tier would remain focused on providing high-quality, transparent, and validated material. This, in turn, would provide a stable foundation upon which national, regional, local, and user-driven innovations can be developed. Such an ecosystem approach would allow forest disturbance monitoring to remain scientifically defensible at the continental scale while also being practically relevant for operational decision-making at local and regional levels.

4.4. Bridging the gap: stakeholder expectations vs. monitoring realities

The synthesis of stakeholder requirements and the current state of the art in Earth Observation (EO) reveals a significant mismatch between the information users desire and what operational systems can currently deliver. Identifying these discrepancies is critical for directing future research and investments, particularly within frameworks like Horizon Europe, to ensure that the next generation of monitoring tools is truly fit-for-purpose.

4.5. The attribution mismatch: driver identification

The most prominent gap identified during the consultation concerns disturbance attribution. Stakeholders consistently ranked the ability to distinguish between natural disturbances (e.g., windthrow, bark beetle outbreaks) and anthropogenic activities (e.g., thinning, clear-cutting) as a primary requirement. However, as highlighted by the technical review of current systems, European NRT monitoring is currently dominated by binary change detection (disturbance vs. non-disturbance). While successful attribution models exist for tropical deforestation, the European landscape is more complex:

- **Thematic subtlety**: distinguishing between a sanitary salvage logging operation and a planned commercial harvest requires high-level contextual information that simple pixel-based change detection often lacks.
- **The role of AI**: emerging deep learning and computer vision architectures show promise in identifying the "spatial signatures" of different drivers. However, these are largely in the research phase and have yet to be operationalized at a continental scale.

4.6. The "Near-Real-Time" reality check

While the term "near-real-time" suggests immediacy, the technical reality in Europe is often one of spatio-temporal irregularity. As noted during the expert discourse, several factors limit the reliability of the "NRT" label:

- **Atmospheric and seasonal gaps**: optical data (Sentinel-2) is heavily restricted by Europe's persistent cloud cover and winter snow. In some regions, NRT can realistically mean waiting months for a clear observation.

— **Terrain shadows**: in mountainous regions like the Alps, low sun angles in winter can affect nearly 30% of forest areas, rendering subtle changes undetectable due to low reflectance.

— **Observation frequency**: unlike radar (Sentinel-1), which provides regular observations, optical monitoring results in a "stuttering" data stream. Communicating this irregularity to users who may expect a steady 5-day update cycle is a significant operational challenge.

4.7. Spatial resolution: aspirational vs. operational

A secondary mismatch exists regarding spatial resolution. As discussed in Section 3, while many users express a desire for ultra-high-resolution data (<50 cm) to detect individual tree stress or "green attack" stages of pest infestation. At present, however, the European operational baseline available through Sentinel-based tier 1 monitoring remains at approximately 10 m spatial resolution.

Delivering meter- or sub-meter-level monitoring at high temporal frequency and continental scale remains challenging under current technical, computational, financial, and data-access conditions. This constraint may change as commercial constellations, cloud computing infrastructure, data-fusion approaches, and AI-based processing workflows continue to develop. For the present, however, this gap reinforces the need for the multi-tiered vision described in Section 4, in which high-resolution requirements are addressed through targeted, on-demand, and bottom-up innovations rather than through a single universal monitoring system.

4.8. Summary of Gaps

The Table 2 summarizes the primary mismatches identified.

Table 2. Primary mismatches identified between assessed stakeholders expectations and characteristics of existing forest disturbance monitoring systems.

Feature	Stakeholder Expectation	Technical Reality (Current)
Attribution	Systematic identification of drivers (Natural vs. Management)	Primarily binary change detection
Latency	Consistent "NRT" (1–7 days)	Irregular; highly dependent on weather/season/topography/latitude
Resolution	Sub-meter (individual tree level)	10–30 m (stand/canopy level)
Reliability	"Guaranteed" updates	Data-driven gaps (clouds, snow, shadows)

Source: JRC analysis based on stakeholder consultation outcomes

Recognizing these limitations does not diminish the value of NRT forest disturbance monitoring; rather, it clarifies where further methodological development and systematic evaluation are most needed. This provides a clear strategic rationale for an in depth intercomparison of existing solutions. By designing a benchmark that explicitly examines areas of mismatch between user requirements and current monitoring capabilities, such intercomparison can assess where different

processing chains perform reliably, where they remain vulnerable, and how performance varies across environmental conditions, disturbance types, and data constraints. This includes, for example, evaluating the robustness of end-to-end workflows in cloud-prone regions, the effects of different cloud-masking strategies, and the sensitivity of algorithms to specific disturbance drivers or disturbance magnitudes. Through such an independent and standardised assessment, evidence can be gathered for improving EO-based forest disturbance monitoring and for better aligning future system development with European policy and operational needs.

5. Artificial intelligence as a catalyst for next-generation monitoring capabilities

By 2026, artificial intelligence (AI) has become a major research focus in Earth Observation, with increasing relevance for large-scale environmental monitoring. In European forest disturbance monitoring, machine learning and deep learning approaches are viewed as important tools for transforming complex satellite time series into the thematic information required by stakeholders.

AI-based methods may help move monitoring systems beyond binary change detection towards more differentiated outputs, including disturbance attribution, severity estimation, and contextual interpretation. In this way, AI could contribute to closing the gap between raw Earth Observation data and the actionable information needed for policy, reporting, management, and risk-related applications.

5.1. AI for disturbance attribution

The most significant contribution of AI may lie in its capacity to analyse the high-dimensional complexity of dense, multi-sensor satellite time series. Established time-series algorithms have proven effective for change detection and heuristic disturbance classification; however, machine learning and deep learning models offer expanded capabilities in automatically identifying subtle spatial, spectral, and temporal signatures across multi-source data streams. This can complement traditional frameworks by improving automated disturbance attribution, helping to distinguish, for example, between windthrow, harvesting, drought-induced decline, insect outbreaks, and mixed or cascading disturbance events.

- **Prospective driver identification**: distinguishing between natural and anthropogenic drivers remains a critical technical hurdle. While AI-driven systems have demonstrated an ability to categorize deforestation drivers in the tropics, for the European landscape, AI could offer a viable path to distinguish subtle "management signatures," such as thinning, from early-stages of natural stressors like drought or bark beetle infestation.
- **Spatial context improves accuracy**: unlike pixel-based methods, Deep Learning architectures (e.g., Convolutional Neural Networks) would be able to recognize the spatial "morphology" of a disturbance. A windthrow event, for instance, might exhibit a distinct spatial signature compared to a geometric clear-cut. If successfully operationalized, AI could categorize these patterns automatically across continental scales.
- **High-quality reference data for agent attribution:** The capacity of AI to attribute specific disturbance agents depends heavily on the availability of specialized training data. Dense, agent-labeled time-series datasets such as the DISFOR dataset (Viehweger et al., 2026) are critical for training and benchmarking models to reliably distinguish between various disturbance agents.

5.2. Plain-language interfaces to democratize data access

AI is also expected to revolutionize the interface between complex monitoring data and non-expert users. A recurring barrier to the uptake of NRT alerts has been the high technical threshold for data manipulation.

Recent developments in Generative AI and Large Language Models (LLMs) have enabled the creation of "Geo-chatbots." These tools could allow users ranging from journalists and policymakers to local forest owners to query monitoring datasets using natural language (e.g., "Summarize storm-related disturbances in the Carpathian region over the last month"). By translating millions of raw data points into concise summaries, AI would serve as a critical democratic layer, potentially making monitoring results accessible far beyond the scientific community.

5.3. New algorithmic frontiers offer scalable, "live" monitoring

A significant recent development is the emergence of GeoAI Foundation Models (e.g., TESSERA, AlphaEarth, TerraMind, THOR) and specialized temporal encoders (Zhu et al., 2026; Feng et al., 2025; Brown et al., 2025; Jakubik et al., 2025; Forgaard et al., 2026). These models are pre-trained on massive quantities of multi-sensor data, which could allow them to be "fine-tuned" for specific monitoring tasks with minimal additional training data.

- **The transition from mapping to monitoring**: while these foundation models have shown good performance in retrospective mapping, their application in an NRT context remains non-trivial. Monitoring requires models to handle "incomplete" or "noisy" time series in real-time; a task that demands higher temporal adaptability and computational efficiency than static mapping.
- **Research focus on "live" inference**: initiatives such as the Horizon Europe project EMBED2SCALE are currently exploring how to leverage these large-scale embeddings. Recent breakthroughs in efficient attention mechanisms (e.g., linear attention or recurrent inference) could significantly reduce the computational burden of processing continental-scale data (Dumeur et al., 2026). Such advances are expected to enable "live" monitoring systems that update incrementally with every new satellite acquisition, rather than reprocessing entire historical sequences.

5.4. AI as a process augmenter

Despite its transformative potential, the consensus within the expert community is that AI would likely not replace the entire monitoring-to-action chain. Its primary role would be that of a filter and prioritizer. In an environment where satellite constellations produce millions of alerts, AI could allow human managers to ignore "business as usual" dynamics and focus limited field resources on the specific events that signify high-risk natural disturbances or regulatory non-compliance.

Ultimately, AI is viewed as an essential catalyst for the Tiered Vision described in Section 4. It could provide the automation necessary for Tier 1 consistency and the specialized, "on-demand" intelligence required for more granular operational responses.

6. Assessing system performance via a collaborative intercomparison challenge

To transition from conceptual frameworks to an operational baseline, the JRC has proposed a large-scale NRT Intercomparison Challenge. While a wide array of monitoring systems exists, comparing their efficacy is currently hindered by divergent validation metrics and differing study areas. This initiative establishes a common, transparent benchmarking framework to identify the strengths and weaknesses of current methodologies across the European continent.

Under this framework, international research groups and system developers are invited to submit their NRT monitoring outputs for a standardized assessment period. Rather than evaluating these algorithms in isolation under optimized local settings, the challenge requires participants to run their methods across a representative variety of European forest biomes. The JRC acts as an independent evaluator, collecting these blind submissions and assessing them against a common benchmark reference dataset specifically designed for this exercise. By centralizing the evaluation process, the challenge will move past self-reported accuracy claims and establish a uniform comparison of how different workflows handle real-world operational difficulties, such as persistent cloud cover, terrain shadows, and varying disturbance sizes. Ultimately, by standardizing these rules of engagement and focusing on the points where current systems diverge, this intercomparison challenge should represent a critical step toward a more transparent, interoperable, and scientifically defensible European forest monitoring landscape.

6.1. An Inventory of Diverse Monitoring Approaches

Prior to the meeting, an inventory of prominent forest monitoring systems was compiled to illustrate the current "galaxy" of available tools. These systems vary significantly in their spectral inputs and operational scales, as well in their logic, which ranges from traditional statistical temporal segmentation to adaptive filters and deep learning.

Table 3. Non-exhaustive inventory of NRT forest monitoring algorithms and systems.

Name / Algorithm	Spatial Res.	Driver Attrib.	Operational Deployment	Key Reference(s)
MoSum/CuSum (BFAST)	10–30 m	No	No (Research)	Verbesselt et al. (2012)
EWMA/EDYN	10–30 m	No	No (Research)	Brooks et al. (2014, 2017)
CCDC / COLD	30 m	No	Partial (USA / Yearly)	Zhu & Woodcock (2014), Zhu et al., (2020)
RADD	10 m	No	Partial (Tropics/EU)	Reiche et al. (2021); van der Woude et al. (2026)
LUCA	10 m	No	Yes (Global)	Mullissa et al. (2024)
DIST ALERT / GLAD	30 m	No	Yes (Global)	Hansen et al. (2016); Pickens et al. (2025)
FNEWs	10 m	Yes	Partial (Germany)	Puhm et al. (2020)
Copernicus HR VPP VDTC	10 m	No	No (upcoming for Europe)	Puhm et al. (2020)
FORDEAD	20 m	No	Partial (France)	Dutrieux et al. (2025)
DETER-RT	10 m	No	Partial (Brazil)	Doblas et al. (2024)
nrt-monitor	30 m	No	No (Research)	Shang et al. (2022)
IQR (in nrt package)	10–30 m	No	No (Python Tool)	Dutrieux & Viehweger (2024)

Name / Algorithm	Spatial Res.	Driver Attrib.	Operational Deployment	Key Reference(s)
S-CCD	30 m	No	No (Research)	Ye et al. (2021)
Dual-form (DL)	10 m	No	No (Research)	Dumeur et al. (2026)
TimesNet RSAD	10–30 m	No	No (Research)	Schiller et al. (2026)
TemporalMatrix	10-20	No	No (Research)	Marinelli et al. (2023)
AVOCADO	10-30	No	No (Research)	Decuyper et al. (2022)
TIIC	30	No	No (Research)	Pelletier et al. (2024)
JJ-FAST	50	No	Partial (Tropics)	Watanabe et al. (2020)

Source: JRC literature review

6.2. Refined sampling design and statistical rigor

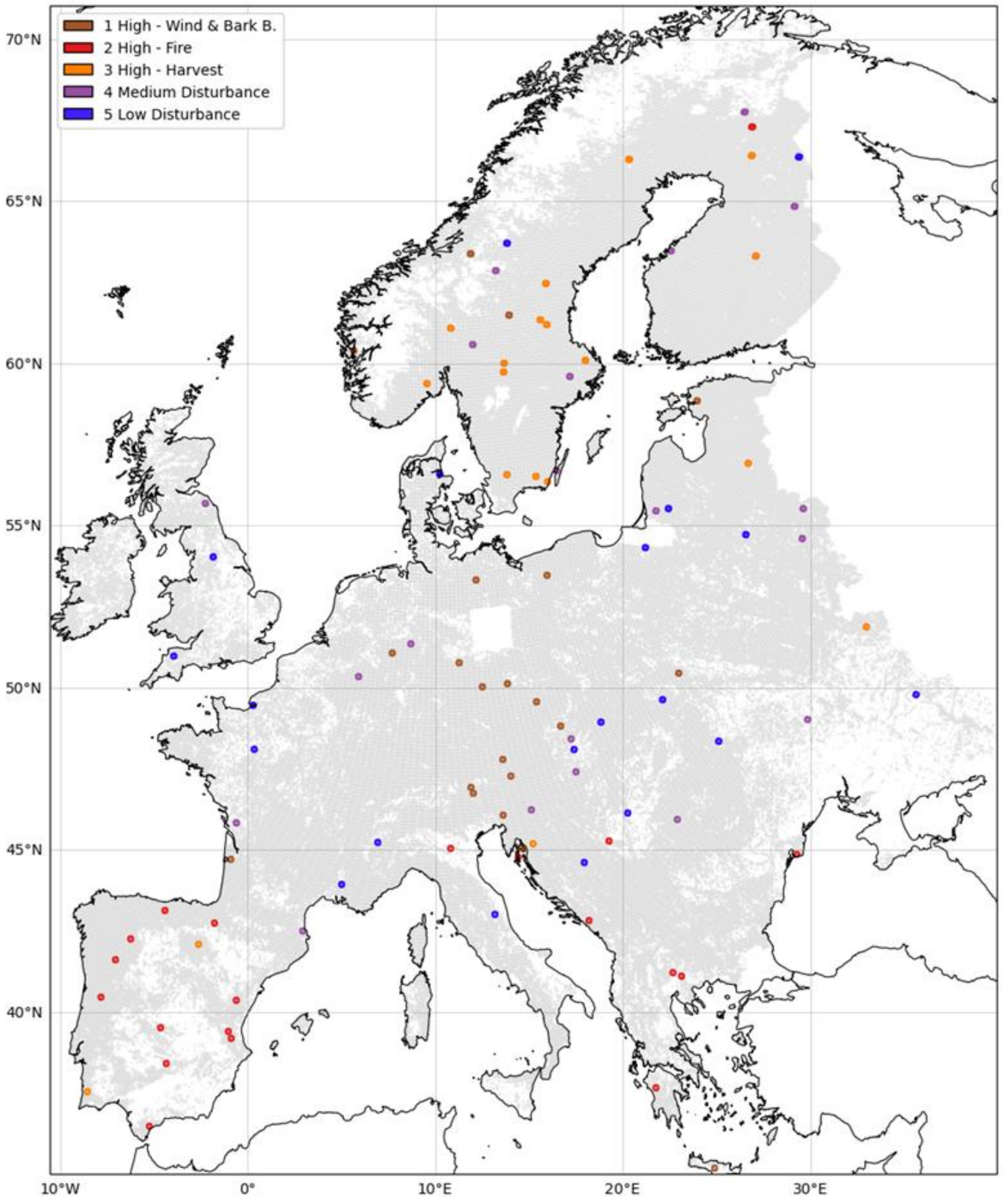
The challenge is designed as a collaborative effort where the JRC serves as an independent evaluator. Following expert feedback, the sampling design was refined to ensure it effectively captures the most challenging dynamics of European forests.

— **Two-stage cluster sampling**: the exercise utilizes 100 Primary Sampling Units (PSU) (5x5 km windows) containing approximately 2000 Secondary Sampling Units (SSU).

— **Entropy-based stratification**: a significant post-meeting refinement involves optimizing the stage-two stratification by targeting areas of disagreement between existing systems. By sampling areas where algorithms yield conflicting results, the benchmark can more effectively highlight the specific drivers of performance variance.

— **Spatial support**: To ensure compatibility with diverse workflows, reference data supports 10, 20, and 30-meter spatial resolutions, matching standard sensor grids such as Sentinel-1/2, Landsat, and HLS.

Figure 2. Map of the 100 Primary Sampling Units used for the NRT methods intercomparison challenge.



Source: JRC analysis

6.3. Response design: beyond binary detection

The "Response Design"; the visual interpretation of change, will go beyond simple "disturbed vs. undisturbed" labels to address the "fitness for purpose" requirements identified by stakeholders.

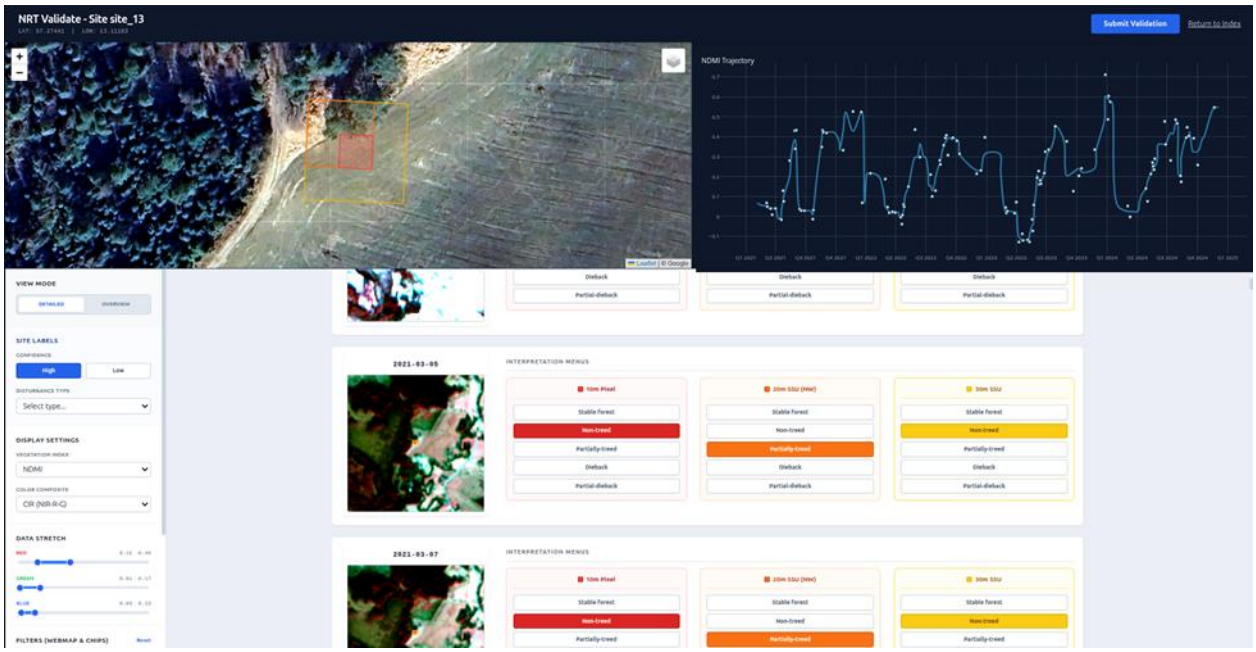
— **Quantifying disturbance intensity**: the reference dataset will characterize disturbances by both spatial extent (low vs. high intensity) and magnitude (subtle dieback vs. structural change).

— **Timeliness and lag metrics**: evaluation will centre on the detection lag versus accuracy curve (Bullock et al., 2022). By assessing performance at specific lag points (e.g., 30, 60, and 120 days), the challenge provides relevant metrics for a range of end-uses.

— **Experimental driver attribution**: while not a mandatory requirement for participants, the JRC will include agent interpretation (e.g., wind, insects, fire) in the reference data to explore the sensitivity of algorithms to specific disturbance types.

To ensure consistency in this process, the JRC has developed a dedicated tool that it will use to visually interpret each sample and create the reference data set.

Figure 3. Example of a HTML static page used for the visual interpretation of Secondary Sampling Units at multiple resolutions.



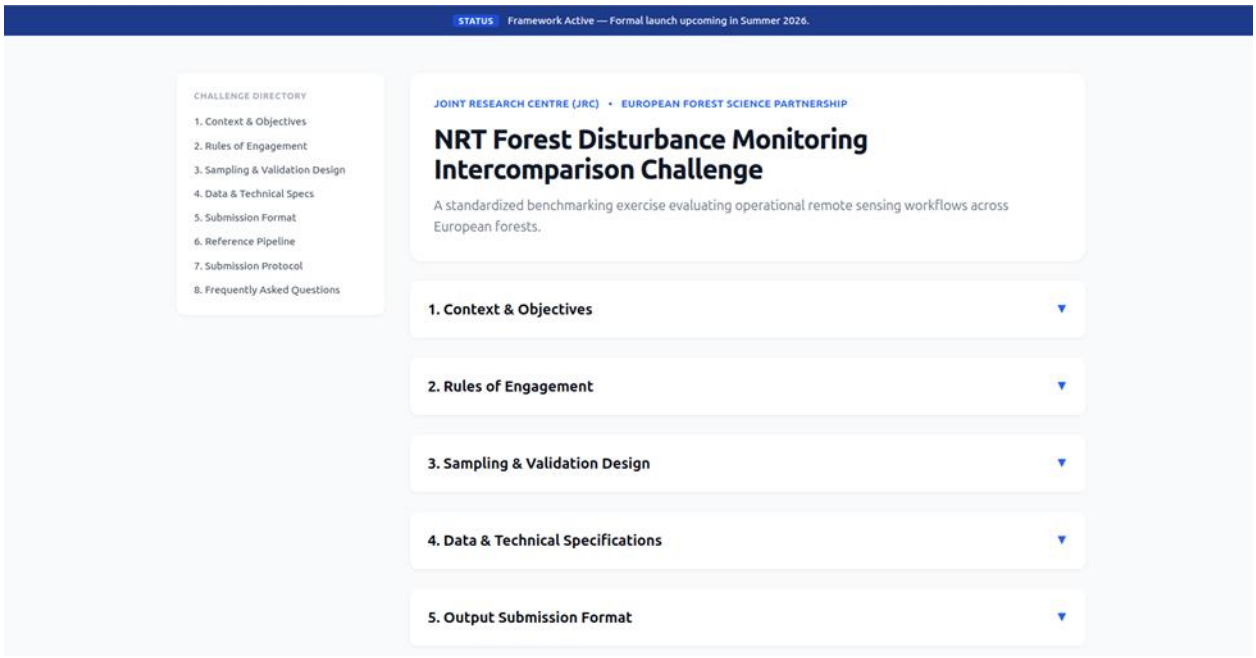
Source: JRC

6.4. Participation and operational practicalities

The challenge focuses on the year 2022 and does not provide a cloud mask, considering cloud masking to be an integral component of an operational NRT system. Participants are therefore encouraged to utilize their own optimized masking workflows across this assessment period.

Furthermore, while the JRC will not provide universal calibration data, it will release a demonstration dataset with reproducible workflows to assist participants in preparing their submissions.

Figure 4. Screen capture of the official NRT Intercomparison Challenge website (launching Summer 2026).



Source: JRC

7. Conclusions: Towards an integrated framework for European forest disturbance monitoring

The expert meeting and stakeholder consultation conducted in early 2026 point towards a clear need for a more integrated and operationally relevant framework for EO-based forest disturbance monitoring in Europe. The transition from retrospective disturbance mapping to NRT monitoring is no longer only a methodological ambition. It is becoming increasingly relevant for supporting climate reporting, biodiversity objectives, risk management, and timely forest management responses. However, the findings also show that no single monitoring system can fully satisfy the diverse requirements of all European user communities. A coordinated, multi-tiered information infrastructure is therefore better suited to aligning technical capabilities with the different mandates, spatial scales, and decision-making timelines of stakeholders.

The results of this consultation emphasise that operational value depends not only on what is technically detectable, but also on whether the resulting information is reliable, interpretable, timely, and actionable. Current Earth Observation systems provide unprecedented volumes of satellite data, yet their usefulness for decision-making depends on the quality and consistency of the derived products. Key requirements identified by stakeholders include methodological transparency, continuity, disturbance attribution, uncertainty information, and compatibility with existing institutional workflows. Addressing current mismatches in spatial resolution, latency, and driver attribution will require continued methodological development, particularly through multi-sensor data fusion, improved time-series analysis, and the targeted integration of artificial intelligence approaches.

The NRT Intercomparison Challenge represents an important next step in this process. By providing a common, scientifically rigorous benchmark, the initiative will enable a more transparent assessment of existing monitoring approaches. Its value lies not only in comparing algorithmic performance, but in identifying the specific environmental, technical, and operational conditions under which different systems perform reliably or remain constrained. This evidence base can support the development of more robust monitoring workflows and help clarify how pan-European institutional monitoring layers, regional services, and local operational tools can function as complementary components of a wider European monitoring ecosystem.

Ultimately, the objective is to support a forest disturbance monitoring landscape that is scientifically defensible, transparent, interoperable, and responsive to the ecological and administrative complexity of European forests. As the initiative moves towards its operational phase, continued collaboration between research institutions, European agencies, national authorities, service providers, and end users will be essential. Strengthening the connection between scientific innovation and stakeholder needs will be critical for ensuring that forest disturbance and forest health information can effectively support policy implementation, carbon reporting, environmental oversight, and the long-term resilience of European forests under rapid environmental change.

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List of abbreviations and definitions

Abbreviations	Definitions
AI	Artificial Intelligence
AVOCADO	Anomaly Vegetation Change Detection
BFAST	Breaks For Additive Season and Trend
CCDC	Continuous Change Detection and Classification
CLMS	Copernicus Land Monitoring Service
COLD	Continuous Monitoring of Land Disturbance
DETER-RT	Real-Time Deforestation Detection System (Detecção de Desmatamento em Tempo Real)
DL	Deep Learning
EEA	European Environment Agency
EFFIS	European Forest Fire Information System
EMS	Emergency Management Service
EO	Earth Observation
EU	European Union
EvoLand	Evolution of the Copernicus Land Monitoring Service
FDM	Forest Disturbance Monitoring
FNEWs	Forest Damage Network Early Warning System (Waldschadens-Frühwarnsystem)
FORDEAD	Forest Degradation and Dieback
GIS	Geographic Information System
GLAD	Global Land Analysis and Discovery (University of Maryland)
HRL	High Resolution Layer
HR VPP	High-Resolution Vegetation Phenology and Productivity
HLS	Harmonized Landsat Sentinel
IQR	Interquartile Range
JRC	Joint Research Centre (European Commission)
LLM	Large Language Model
LUCA	Land Use Change Alert
LULUCF	Land Use, Land-Use Change, and Forestry
ML	Machine Learning
MRV	Measurement, Reporting, and Verification
NFI	National Forest Inventory
NGO	Non-Governmental Organization
NRT	Near-Real-Time
PSU	Primary Sampling Unit
RADD	Radar for Detecting Deforestation
RSAD	Reconstruction-based Spectral Anomaly Detection
SAR	Synthetic Aperture Radar
S-CCD	Stochastic Continuous Change Detection
SSU	Secondary Sampling Unit
UAV	Unmanned Aerial Vehicle

Abbreviations	Definitions
VDTC	Vegetation Disturbance Tree Cover
VHR	Very High Resolution

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Annexes

Annex 1. Online survey

Welcome to our survey!

This survey is part of a project carried out in collaboration with the Joint Research Centre (JRC) of the European Commission. The objective of the project is to better understand the requirements of different user communities for Near Real-Time Forest Disturbance Monitoring (NRT FDM) systems in Europe.

The purpose of this survey is to capture your priorities, information needs, and technical requirements related to NRT FDM, based on your professional role and experience. The results will help inform the design of future European NRT FDM systems that are fit for purpose for different user communities. As this survey is addressed to respondents across multiple European countries, it is conducted in English.

The survey takes approximately 10-12 minutes to complete.

Section A: Your role, priorities, and use of near real-time forest disturbance information

The following questions ask about your professional background, the forest disturbances most relevant to your work, and how you currently use—or would use—near real-time forest disturbance information. This helps us understand your priorities and context when interpreting the answers that follow.

A1. Which of the below best describes the organisation you are working for?

- ☐ National forest authority or national environmental agency
- ☐ Regional / local forest management or regional / local protected area authority
- ☐ Research institute or higher education institution
- ☐ Forestry company or large private forest owner
- ☐ EU institution or Copernicus Services
- ☐ Insurance company
- ☐ Carbon-market actors
- ☐ NGO or environmental oversight organisation
- ☐ Other (please specify)

Other (please specify)

A2. In which country are you located/ is the majority of your work on forest disturbances taking place?

A3. Which forest disturbances are most relevant for your work/ the forests you are working with?

- ☐ Storm damage or windthrow
- ☐ Forest fires
- ☐ Pest or disease outbreaks
- ☐ Invasive alien species
- ☐ Drought-related decline or mortality
- ☐ Timber harvest/ clear cut
- ☐ Thinning
- ☐ Gradual degradation or subtle change
- ☐ Complex or mixed disturbances

A4. What are your main uses for NRT forest disturbance information?

- ☐ Rapid awareness of forest disturbances
- ☐ Operational decision-making and forest management (Short-Term: Days to 1 year)
- ☐ Tactical decision-making and forest management (Medium-Term: 1–10 years)
- ☐ Strategic decision-making and forest management (Long-Term: >10-90+ years)
- ☐ Policy support
- ☐ Greenhouse gas emmissions assessment
- ☐ Risk assessment/ Impact evaluation
- ☐ Research/ Scientific analyses
- ☐ Transparency/ Oversight/ Public communication

Other (please specify) ☐

Other (please specify)

A5. Which data formats or standards do you typically work with?

- GeoTIFF / Cloud Optimised GeoTIFF (COG) ☐
- Vector formats (e.g. GeoJSON, Shapefile) ☐
- Hyperspectral (BSQ, HSZ, ENVI, HDF5, NEON, TIFF …) ☐
- LiDAR (LAS, LAZ, E57, ZLAS, …) ☐
- Tabular formats (CSV, Excel) ☐
- STAC or catalog-based access ☐
- Other (please specify) ☐

Other (please specify)

A6. Please provide us with any additional information on your current use of forest disturbance information - particularly information from Earth observation data - which you find relevant for describing your work.

Section B: Information Requirements

Resolution in Earth observation defines the level of detail and clarity in imagery or data caprured by sensors on drones, satellites or aircraft, as well as ground-based sensors. It is not a single measurement but is categorized into four main types - spatial, spectral, temporal, and radiometric—which together determine how useful the data is for specific applications.

The following questions will address your information requirements in an ideal world. Your answers should not be limited by the data types and resolutions you currently have access to, but should aim to give us an understanding of what could help you in your work.

B1.

What spatial resolution would be most useful for your work?

Spatial resolution refers to the size of the smallest object or feature that can be detected and represented in the data.

- Ultra-high resolution (≤ 15 cm): Very fine spatial detail, enabling the detection of individual trees, small canopy gaps, and fine-scale forest disturbances. ☐
- Very high resolution (16 cm – 50 cm): Allows identification of individual tree crowns, small harvest areas, windthrow patches, and narrow linear features such as skid trails or forest roads. ☐
- High resolution (50 cm – 1 m): Suitable for mapping forest stands, clear-cuts, larger windthrow areas, and major infrastructure, and for supporting detailed disturbance attribution. ☐
- Medium resolution (1 m – 30 m): Commonly used for operational forest monitoring, disturbance mapping, and greenhouse gas assessments at regional to national scales (e.g. Sentinel-2 at 10 m). ☐
- Low / coarse resolution (> 30 m): Appropriate for large-scale or global assessments of forest change, trends, and emissions, but with limited ability to detect small or heterogeneous disturbances (e.g. MODIS, Landsat). ☐
- Other (please specify) ☐

Other (please specify)

B2.

What temporal resolution would be most useful for your work? ***Temporal resolution refers to the frequency at which sensors recapture the exact same location. It defines how often data is updated.***

- ☐ Daily (high temporal resolution)
- ☐ Every 2–3 days
- ☐ Weekly
- ☐ Bi-weekly to monthly
- ☐ Bi-annually (every 6 months)
- ☐ Annually (low temporal resolution)
- ☐ No specific requirement

B3.

In relation to the temporal resolution at which data is collected, how quickly after a disturbance would information about it have to be made available to you to be most useful?

(eg. if after data collection a pre-processing step is required before data is made available to end users).

- ☐ Within hours
- ☐ Within 1 day
- ☐ Within 2-3 days
- ☐ Within 3–5 days
- ☐ Within 1 week
- ☐ Within multiple weeks, less than a month
- ☐ Monthly
- ☐ Bi-Annually (every 6 months)
- ☐ Annually
- ☐ Not critical for my use case
- ☐ Other

Other

B4. **Which types of outputs from a near real-time forest disturbance monitoring system would be most useful for your work?**

- ☐ Alerts or notifications (e.g. rapid warnings of new or ongoing disturbances)
- ☐ Spatial products (maps) (e.g. disturbance extent, location, or severity)
- ☐ Time series or change trajectories (e.g. disturbance dynamics or recovery over time)
- ☐ Indicators or aggregated statistics (e.g. summaries at stand, regional, or national level)
- ☐ Access to underlying data (e.g. pixels, features, or downloadable datasets for further analysis)

Other (please specify)

Other (please specify)

B5.

Please provide us with any additional information on your desired of forest disturbance information - particularly information from Earth observation data - that you find relevant for your work.

Section C: Operational use, formats, and system integration

This section explores how you use NRT forest disturbance information in your work, the level of detail you require, and how information *should* be delivered and integrated into existing workflows or systems.

C1. How would you primarily use near real-time forest disturbance monitoring (NRT FDM) products?

- Visual inspection (e.g. maps, dashboards)
- Reports or summaries (e.g. regular briefings, situation reports)
- Automated workflows or decision-support workflows
- Integration into existing national or organisational information systems
- Research or analytical workflows
- Other (please specify)

Other (please specify)

C2. What level of thematic detail should a NRT FDM product/ system provide?

- Binary change detection (e.g. disturbance vs. no disturbance)
- Classification of disturbance type (e.g. fire, windthrow, harvest)
- Estimation of disturbance severity or magnitude
- Confidence or uncertainty information (e.g. quality or reliability metrics)
- Other (please specify)

Other (please specify)

C3. How would you prefer to access NRT FDM products?

- Interactive web interface or dashboard
- Downloadable GIS layers or data products
- API or machine-to-machine access
- Reports or summaries
- Automated alerts or notifications (e.g. email, system alerts)
- Other (please specify)

Other (please specify)

C4.

Should an ideal NRT FDM system be interoperable with existing national or organizational systems?

- Yes
- No

C5.

Briefly explain why interoperability with existing systems is important for your work, and what this interoperability should include.

If applicable, please specify the system(s) currently used in your country or organisation.

C6.

Briefly explain why interoperability with existing systems is not required for your work or use case.

If relevant, you may also indicate whether you currently rely on stand-alone tools or workflows, or why integration with existing systems would not add value.

Section D: Final reflections and additional considerations

This final section gives you the opportunity to share any additional insights, considerations, or recommendations that may be important for the development of a near real-time forest disturbance monitoring (NRT FDM) system scalable across Europe.

D1.

What key aspects should be considered when developing a near real-time forest disturbance monitoring (NRT FDM) system that can be scaled across Europe?

Please feel free to comment on technical, operational, institutional, or policy-related aspects that you consider important.

D2.

Is there anything else you would like to add, or any aspect we may have overlooked?

Please use this space for any final comments or suggestions

Thank you for your participation!

Annex 2. Semi-structured interview guide

Interview Metadata

- Date: XX.XX.XXXX
- Time: XX.XX-XX.XX
- Interviewee: *(Title) First name Last name*
- Affiliation: *Name*
- Interviewer: *(Title) First name Last name*
- Recording consent given**:** ☐ Yes ☐ No

1 – Goals & Priorities

Key goals

- What are you / would you be using NRT forest disturbance information for?
- Do you have access to sufficient/adequate data and information concerning forest disturbances? / Do you need more? / What would you like to be alerted about?

Priorities

- What are your priorities in relation to the mentioned use?

Add on:

- Which disturbance types are most critical for you (e.g. storms, harvests, pests, drought, fire events)?
- How do you define "near real-time" in the context of your use (e.g. days, weeks)?
- How important is timeliness for your use case?
- How important is thematic detail for your use case?

2 – Data Characteristics: Type, Resolution, Frequency

- What characteristics does the FDM data have that you currently use?
- What characteristics would the ideal NRT FDM system have to be useful for your purposes? (data type, spatial detail, and update frequency)

Add on:

- Data type: Do you mainly need alerts, maps, indicators, time series, or access to raw data?
- Spatial detail: At what minimum spatial unit does disturbance information become actionable for you (e.g. single tree level, stand, region)?
- Frequency / latency: How quickly after a disturbance would information still be useful for your work (e.g. daily, weekly)?

3 – Outputs, Formats & Integration

- How would you ideally like to access, receive, and use NRT FDM information and/ or information systems?

Add on:

- In which formats or platforms would outputs be most useful to you (e.g. maps, reports, dashboards, APIs)?
- What minimum confidence level do you require alongside disturbance information (precision vs. accuracy)?
- Should outputs be compatible with existing national or organizational systems?
- Which action would you take after receiving that information?
- Would you prefer a highly accurate map that arrives after two months or a slightly less certain 'alert' that arrives within 48 hours but may include some false alarms?

4 - What else do you think someone must know - or must consider - who was to develop a NRT FDM system (which can be scaled across Europe)?

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