FUTUREFOR

Copernicus Applications for Next-Generation Forest Monitoring

Deliverable 2.1

Stakeholder Report

Stakeholder and Legislation Analysis

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Deliverable abstract	The FUTUREFOR project's Deliverable D2.1 provides a comprehensive analysis of the stakeholder landscape and legislative context for advancing Earth Observation (EO) and Remote Sensing (RS) in European forest monitoring. Responding to the proposed EU Forest Monitoring Regulation, the report synthesises input from a broad range of stakeholders - including public authorities, research organisations, and private sector actors - through surveys and policy reviews. The report identifies principal barriers to EO/RS adoption (technical complexity, financial constraints, concerns about data sovereignty). The analysis also maps current monitoring and reporting processes, detailing the interplay between EU-level frameworks (such as LULUCF, EUDR, and the Renewable Energy Directive) and national forest inventory practices. The report concludes with recommendations for harmonised, INSPIRE-compliant workflows, hybrid estimation approaches for LULUCF reporting, and targeted capacity-building initiatives. These findings directly inform the technical developments in FUTUREFOR, ensuring alignment with evolving policy requirements and supporting the transition toward more harmonised, timely, and policy-relevant forest monitoring across Europe.
Keywords	FUTUREFOR, Forest Monitoring Regulation, EU Legislation, Stakeholder Analysis, Data Harmonisation

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ACRONYMS LIST

AI	Artificial Intelligence
ALS	Airborne Laser Scanning
CLC	CORINE (Coordination of Information on the Environment) Land Cover
CLMS	Copernicus Land Monitoring Service
DLT	Dominant Leaf Type (Copernicus HRL product)
EEA	European Environment Agency
EFFIS	European Forest Fire Information System
EFISCEN	European Forest Information SCENario Model
EO	Earth Observation
EU	European Union
EUDR	EU Deforestation Regulation (Regulation on deforestation-free products)
FAO	Food and Agriculture Organisation of the United Nations
FRL	Forest Reference Level
FMR	Forest Monitoring Regulation
FRP	Fire Radiative Power
FRA	Forest Resources Assessment (FAO initiative)
FTY	Forest Type (Copernicus HRL product)
GDPR	General Data Protection Regulation
GFAS	Copernicus Atmosphere Monitoring Service's Global Fire Assimilation System
GHG	Green House Gas
GIS	Geographic Information Systems
HRL	High Resolution Layer (Copernicus product series)
HR-VPP	High-Resolution Vegetation Phenology and Productivity
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
INSPIRE	Infrastructure for Spatial Information in Europe (EU directive)
LiDAR	Light Detection and Ranging
LULUCF	Land Use, Land-Use Change, and Forestry
ML	Machine Learning
MMU	Minimum Mapping Unit
NDVI	Normalised Difference Vegetation Index
NFAP	National Forestry Accounting Plan (LULUCF)
NFI	National Forest Inventory
NRR	Nature Restoration Regulation
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RED III	Renewable Energy Directive III
RS	Remote Sensing

S3	Sentinel 3
SAR	Synthetic Aperture Radar
SDG	Sustainable Development Goal (UN framework)
SMEs	Small and Medium Enterprises
TCD	Tree Cover Density (Copernicus HRL product)
UAV	Unmanned Airborne Vehicle

1. INTRODUCTION

1.1. FUTUREFOR project overview

Forests play a pivotal role in Europe's climate, biodiversity, and bioeconomy objectives, yet their sustainable management increasingly depends on advanced monitoring and reporting systems (EC, 2023; EEA, 2024). The FUTUREFOR project, funded under the European Union's Horizon Europe research and innovation programme (Grant Agreement No. 101180278), addresses this need by integrating state-of-the-art Earth Observation (EO) and Remote Sensing (RS) technologies into operational forestry management, with a focus on aligning technical innovation to evolving EU policy frameworks such as the Biodiversity Strategy 2030, LULUCF Regulation, and the proposed Forest Monitoring Regulation (FMR) (EC, 2020; EC, 2023).

Recent advances in remote sensing technologies have greatly enhanced the capacity for large-scale, consistent forest monitoring across Europe, enabling timely detection of changes in forest cover and supporting EU policy objectives (DIASCA Forest Monitoring Guidance). For a comprehensive review of these applications, see de Wergifosse et al. (2022).

FUTUREFOR brings together eight partners from across Europe, combining expertise in forest monitoring, Copernicus services, artificial intelligence, and big data analysis. The consortium includes research institutions, technology providers, and end-users to ensure that the developed solutions address real-world challenges and policy needs.

With the increasing challenges facing European forests due to climate change, biodiversity loss, and growing societal demands, there is an urgent need for more comprehensive, harmonised, and timely monitoring systems. FUTUREFOR addresses this need by assessing current practices, identifying user requirements, and developing technical solutions that can be implemented at both European and national levels.

Despite the technological promise of Copernicus satellite systems and related digital tools, widespread adoption in forestry remains limited by technical complexity, fragmented data standards, and institutional inertia (Puhm et al., 2023; Speranza et al., 2023; Fassnacht et al., 2024). Addressing these challenges requires not only robust technical solutions but also targeted capacity building and inclusive stakeholder engagement (FUTUREFOR Stakeholder Survey, 2025; FORWARDS MS8, 2024).

The FUTUREFOR project is structured around a series of pilot studies designed to develop, test, and validate innovative forest monitoring products and services using Copernicus data and advanced remote sensing technologies (Table 1). These pilots are implemented across diverse European locations to ensure relevance and scalability.

Table 1 The FutureFor pilot studies/services

Pilot study	Focus/Objective
Forest disturbance/regeneration/restoration	Time series and deep learning for disturbance and recovery
Forest Digital Twin	User-friendly digital platform for private forest owners
Fire risk indices, 24h real-time wildfire detection/monitoring, seasonal fuel mapping	Rapid, high-frequency wildfire detection and monitoring, early warning maps for wildfire risk, Alerts and impact delineation for monitored areas, AI-enabled seasonal updates of European fuel maps
Forest biomass for bioenergy	Biomass estimation for sustainable bioenergy

The technical feasibility of the pilots is tested and validated across Austria, Denmark, France, Germany, Italy, and Ukraine to ensure broad applicability and support the upcoming EU Forest Monitoring Regulation. The pilots are then refined into operational services. FUTUREFOR responds by prioritising user adoption through co-designed services-such as disturbance detection, digital twins for forest condition monitoring, fire risk mapping, and biomass estimation-that directly support policy compliance and operational efficiency.

FUTUREFOR also aims to demonstrate the economic potential of open forest data through the development of concrete business cases. The three detailed business cases are the forest digital twins for private forest owners, critical infrastructure for wildfire risk, and biomass mapping for bioenergy (Table 2). The forest disturbance module (e.g., pest outbreaks, storm damage) is not proposed as a standalone business case in the FUTUREFOR project due to market readiness challenges and policy-driven prioritisation.

Table 2 The FutureFor business cases

Business case	Description
Forest Digital Twin for private owners	Digital twin platform for sustainable private forest management
Critical infrastructure wildfire risk	Geofencing and alerts for utility operators on wildfire risk
Biomass mapping for powerplant optimisation	Toolkit for regulatory compliance, resource mapping, and operational support

The demand for disturbance management services remains fragmented because, unlike wildfire risk or biomass estimation—where clear beneficiaries such as energy companies and utilities drive investment—stakeholders like smallholders and NGOs lack a unified funding mechanism to support such efforts. Additionally, the benefits of addressing disturbances like pest outbreaks or restoring carbon stocks tend to unfold over long periods, often spanning decades, which discourages private investors seeking quicker returns. Furthermore, while

policies such as the EU Biodiversity Strategy mandate disturbance mitigation, these measures are typically not directly monetized, thereby diminishing the economic incentives necessary for developing sustainable commercial services in this domain.

These business cases are designed to be close to market, responding to identified needs in the bioenergy sector, critical infrastructure management, and private forestry. They are developed in parallel with the technical pilots and are demonstrated to end-users to test value propositions and market fit.

This deliverable (D2.1) under Work Package 2 (WP2) assesses the current EO/RS uptake and applications in European forestry identifying both the status quo and critical gaps in operationalisation. Stakeholder needs across different fields are mapped and prioritised to ensure relevant and scalable solutions. The report also identifies **technical, institutional, and financial barriers** to the adoption of EO/RS tools, drawing on survey data and targeted engagement activities. Finally, it aims at delivering actionable insights to advance the operationalisation of EO/RS in European forestry, bridging the gap between legislative ambition and practical implementation (CHRMP, 2024; FORWARDS MS8, 2024; EC, 2023)

The report is structured into 6 sections:

Section 1: General introduction of the FutureFor project objectives

Section 2: EU Forest Policy Framework outlines the legislative drivers and reporting requirements shaping the need for advanced forest monitoring, with a focus on the Forest Monitoring Regulation and its linkages to other key EU policies.

Section 3: Stakeholder analysis and engagement strategy, describes the methodology and findings of stakeholder mapping, categorisation, and engagement planning, highlighting the roles and priorities of different actor groups.

Section 4: Policy-technology integration analysis, maps EO/RS capabilities to legislative requirements, identifies validation gaps, and outlines the project's approach to bridging policy-implementation divides.

Section 5: Adoption barriers-a multi-dimensional analysis, examines technical, institutional, and financial obstacles to EO/RS uptake, based on survey evidence and case studies.

Section 6: Strategic framework for enhanced EO/RS adoption synthesises findings into actionable strategies, including tailored engagement, capacity-building initiatives, and policy-aligned service deployment.

2. EU forest policy framework: regulatory drivers for Earth Observation

EU forest governance under the Green Deal combines binding legislation and voluntary initiatives to address deforestation, carbon accounting, and biodiversity loss. These policies

face implementation hurdles, such as resolution mismatches (e.g., Copernicus CLC+ Backbone's 100m grids misclassifying 30% of Baltic peatlands) and the "validation paradox," where 88.9% of researchers prioritise manual surveys over AI-validated EO products despite lower costs. FUTUREFOR addresses these gaps by aligning its services with legislative requirements, as detailed in Section 4.1.

The FMR calls for a new era regarding the collection of forest variables. It may offer substantial benefits to various EU forest-related policies, including those without explicit formal reporting obligations. The FMR expects to provide more timely, comprehensive, and harmonised data on forest conditions across the EU using advanced technologies such as remote sensing, and forest information from NFIs and other existing forest monitoring systems (EC 2023a). By doing so, it expects to enhance policy design, implementation, and impact assessment across multiple forest-related policy areas.

The FMR aligns with the EU Forest Strategy. It supports sustainable forest management, biodiversity protection, and climate change mitigation/adaptation by supplying comprehensive data that facilitates tracking progress towards the Strategy's goals. The FMR aims to support several major EU forest-related policies, as shown in Table 3 and Table 4. The EU Biodiversity Strategy 2030 to support the assessment of biodiversity targets and old-growth forest protection (EC 2020); the EU Climate Policy/European Climate Law to enhance the LULUCF reporting on forest carbon stocks (EU 2021a); the Renewable Energy Directive to provide data on forest biomass resources and sustainability (EU 2023).

However, only a few of these are explicitly stated to have formal reporting obligations. The main ones of relevance also to the use of EO/RS are the Land Use, Land Use Change and Forestry (LULUCF), the EU Regulation on Deforestation-free products (EUDR) Regulation, the Habitats Directives, the Renewable Energy Directives (RED II and RED III), and the Corporate Sustainability Reporting Directive (CSRD). Table 3 summarises which indicators are reported under these policies. In particular, the LULUCF Regulation, which mandates extensive reporting on forest-related activities and carbon stocks, is expected to benefit significantly from the proposed Forest Monitoring Regulation (FMR). Both regulations report on forest area, carbon stocks, and forest health, ensuring consistency and reliability in data collection.

Enhanced FMR could aid in tracking progress towards the LULUCF sector's contribution to climate neutrality by 2035 and net negative emissions thereafter. The FMR would help simplify complex accounting rules, such as the Forest Reference Level setting process, and address gaps in national monitoring systems. Remote sensing data, obtained from aerial or satellite imagery like Earth Observation tools and digital data from programs like Copernicus, offer extensive spatial coverage and can capture various forest attributes across large areas. The FMR propose the use of advanced technologies to, i.e., ensure that data on carbon stocks and fluxes are

more accurate, enabling Member States to report LULUCF emissions and removals more precisely.

This framework represents a critical step toward sustainable forest governance, yet its success hinges on resolving technical disparities, enhancing stakeholder collaboration, and aligning voluntary initiatives with legislative mandates. As the EU navigates these challenges, EO technologies and cross-sector data sharing will play pivotal roles in achieving climate and biodiversity targets.

FUTUREFOR's success hinges on active stakeholder involvement to ensure increased uptake tools meet real-world needs while adhering to legislative frameworks. The project directly targets implementation gaps between EU forest legislation and real-world practice through its three core services and business cases:

FUTUREFOR bridges legislative-implementation gaps by integrating Earth Observation data (Sentinel-1, Sentinel-2) with national forest inventories, airborne laser scanning, and targeted field sampling through hybrid AI-driven workflows. This approach ensures policy-compliant tools for deforestation monitoring, dynamic forest condition assessments via digital twins, and biomass mapping for sustainable resource planning, transforming EO/RS into a scalable backbone for EU forest governance.

Regarding the four core services, the disturbance monitoring system for FMR and EU Deforestation Regulation's (EUDR) compliance will integrate Sentinel-1 radar and Sentinel-2 optical data to detect windthrows /deforestation events smaller than 0.5 hectares. Regarding the EUDR needs, this service will surpass the 1-hectare detection threshold with high accuracy. This hybrid approach combines AI-driven preprocessing with targeted field sampling, supporting both compliance and operational efficiency.

For Forest Monitoring Regulation (FMR) compliance, the Digital Twins service delivers a spatially explicit, continuously updated representation of forest condition by integrating Sentinel-2 Earth Observation data with national forest inventory and management datasets, enabling stakeholders to visualise, monitor, and assess forest status and changes for scenario analysis and policy support.

The fire risk module

The biomass optimisation module in FUTUREFOR delivers EO-based mapping and monitoring of forest biomass by integrating Sentinel satellite data, airborne laser scanning, and ground inventory information. This service supports sustainable resource planning, timber stock estimation, and bioeconomy strategies, providing stakeholders with actionable intelligence for regulatory reporting and supply chain optimisation in alignment with EU sustainability goals.

Table 3 Legally binding forest-related reporting

Legislative Focus	Policy	Key monitoring parameters	Spatial/Temporal requirements	Examples of potential FMR integration	Reference
Biodiversity	Habitats Directive	- Habitat range - Species population trends - Conservation measures	10m resolution for habitat mapping 6-year reporting	Sentinel-2 time series analysis	Directive 92/43/EEC, Article 17
Climate	LULUCF Regulation	- Carbon stocks (biomass, soil) - Harvested wood products	Annual reporting 100m aggregation for Tier 3 compliance	NFI-EO fusion	Regulation (EU) 2018/841 Regulation - 2021/1119 - EN - EUR-Lex
Trade	EUDR	- Geolocation of commodities - Deforestation-free certification	<50m accuracy Real-time supply chain tracking	Sentinel-1/2 hybrid ML models	Regulation (EU) 2023/1115
Energy	RED III	- Biomass sustainability metrics - GHG savings from bioenergy	30m resolution for plantation mapping	Digital twins for biomass yield projections *)	COM/2021/557 final
Corporate	CSRD[4]	- Carbon stock changes - ILUC impacts	Entity-level reporting Annual disclosures	EO validation workflows	Directive (EU) 2022/2464

*) Note: Digital twin ecosystems extend beyond biomass monitoring to support multi-objective forest analysis, enabling biomass yield optimisation, carbon stock quantification, climate resilience modelling, disturbance prediction, and biodiversity impact assessment (Mottus et al., 2024). Their adaptability makes them essential for scenario analysis and adaptive forest management.

[4] although the Omnibus package (2025) proposes reduced scope and delayed reporting.

Table 4: Examples of main non-legally binding forest-related reporting

Initiative type	Policy framework	Operational programme	Objectives	Monitored indicators	Reporting mechanism	Potential FMR contribution
Sustainability	EU Forest Strategy 2030 COM(2021) 572 final	Proposed Regulation on a Forest Monitoring Framework	Enhance forest resilience and biodiversity	- Forest connectivity - Deadwood volume	INSPIRE-compliant dashboards	Fragmentation indices for connectivity maps
Economic	EU Bioeconomy Strategy Bioeconomy strategy - European Commission	European Forest Accounts Eurostat EFA	Quantify forestry's economic contribution	- Timber flows - Employment data	Automated NFI-EO data harmonisation	Biomass valuation models
Global	Global Forest Resources Assessments | Food and Agriculture Organization of the United Nations	Remote Sensing | Global Forest Resources Assessments | Food and Agriculture Organization of the United Nations	Track global forest resources	- Forest area - Carbon stocks	Hybrid MODIS-LiDAR baselines	EU forest regeneration and restoration data

2.1. Forest Monitoring Regulation: central policy connections

The Forest Monitoring Regulation (FMR) is intended to serve as a **centralised data backbone** for EU forest governance, harmonising reporting requirements and enabling compliance with multiple policies. By standardising data collection on forest structure, health, and ecosystem services, and integrating Earth Observation (EO), National Forest Inventory (NFI) data, and advanced analytics, the FMR aims to bridge the gaps between fragmented legislative frameworks, ensuring coherence in addressing deforestation, biodiversity loss, and climate targets.

Nature Restoration Law (NRL): the FMR variables on standing/lying deadwood (≥30 m^3/ha), uneven-aged forest structures (≥40% canopy layer diversity), and forest connectivity (≥500m corridors) directly support NRL's Article 10 targets (IEEP, 2023; EC, 2021). Satellite-derived biomass maps (10m resolution) and LiDAR canopy height models enable Member States to quantify restoration progress for the six mandatory indicators (EC, 2024; EC, 2020).

Deforestation Regulation (EUDR): the FMR's geolocation-capable Earth Observation (EO) system provides <50m accuracy tracking of logging activities, enabling operators to demonstrate compliance with Article 9's deforestation-free requirements. Cross-referencing FMR data with national cadastral systems allows automated verification of EUDR's due diligence statements (EC, 2024; Schier et al., 2022).

Furthermore, the FMR enhances LULUCF's carbon accounting through the LULUCF's Tier 3 reporting requirements and addresses the CRCF's permanence requirements through quarterly biomass change detection, disturbance alerts (<30-day latency for fires/storms), and 20-year carbon stock projections (IEEP, 2023; Luik, 2024)

Finally, the FMR enables tracking of **the EU Biodiversity** Strategy's Target 1 through primary forest mapping (with high detection accuracy), protected area effectiveness assessments (β-diversity indices), and invasive species spread modelling (30m habitat suitability maps) (EC, 2020).

Table 5 FMR data applications across key EU policies

Policy instrument	Required FMR variables	Compliance use case	Technical synergy
NRL (Art.10)	Deadwood volume, canopy structure diversity	Annual restoration progress reports	LiDAR structural metrics enhance Sentinel-2 spectral analysis for deadwood mapping; shared infrastructure reduces monitoring costs across restoration sites (IEEP/NRR, 2024)
EUDR	10-day deforestation alerts, species-specific biomass maps	Automated due diligence certification	Copernicus CLMS high-resolution layers provide standardised land cover baselines; automated change detection algorithms enable real-time deforestation alerts for supply chain verification (EUDR, Schier 2023)
LULUCF	Species-specific carbon stock trajectories, harvest residues	FRL *) baseline adjustments	FMR species composition data calibrates EFISCEN*) model parameters; harmonised biomass equations improve FRL *) accuracy and reduce reporting uncertainties across Member States (Forsell et al., 2018; Regelmann, 2023)
CRCF	Disturbance-resistant carbon accounting, additionality baselines	Permanence buffer calculations	Permanence risk algorithms integrate disturbance probability maps with carbon stock trajectories; baseline methodologies align with LULUCF accounting rules for consistency (EU CRCF)
Biodiversity Strategy	Forest integrity indices, fragmentation metrics	Protected area gap analysis	Multi-scale fragmentation metrics from FMR complement protected area connectivity analyses; forest structural indices provide standardised integrity assessments beyond current inventories (EC, 2020; Fischer et al., 2023)

*) EFISCEN model(s), European Forest Information SCENario Model, is a large-scale forest model that projects forest resource development on regional to European scale.

*) FRL: Forest Reference Levels are benchmarks set by each EU Member State to project and account for future net greenhouse gas emissions and removals from managed forests, based on the continuation of forest management practices from a specified reference period (typically 2000–2009). They serve as the baseline against which actual forest sector emissions and removals are compared under the EU's Land Use, Land-Use Change and Forestry (LULUCF) Regulation

2.1. Harmonised reporting requirements across EU policies

EU forest-related policies impose diverse yet partially overlapping reporting obligations, presenting both opportunities for integration and challenges in data harmonisation. The temporal requirements vary significantly across legislative instruments: the Nature Restoration Law (NRL) mandates triennial reporting on six forest indicators commencing in 2026, while the LULUCF Regulation combines five-year National Forestry Accounting Plan (NFAP) updates with annual carbon flux reporting. In contrast, the EU Deforestation Regulation (EUDR) necessitates real-time geolocation data submissions for each commodity batch, and the Carbon Removal Certification Framework (CRCF) requires decadal certification supplemented by annual verification snapshots. These divergent timelines create complexities for Member States in synchronising monitoring efforts across policy domains.

Spatial resolution requirements further illustrate the fragmentation: the Biodiversity Strategy demands 0.1-hectare precision for primary forest mapping in protected areas, whereas the EUDR applies a 1-hectare minimum mapping unit for commercial forests. The CRCF adopts an intermediate approach, permitting 10-hectare aggregation units for carbon project reporting. Such disparities in mapping precision risk creating data silos, particularly for cross-border forests subject to multiple regulatory frameworks.

This analysis underscores the imperative for technical solutions that reconcile granularity needs with operational feasibility, ensuring the Forest Monitoring Framework can serve as a unified data backbone for multifunctional reporting.

Key variable overlaps

Analysis reveals 14 shared variables across policies:

Table 6 Cross-policy variable alignment

Variable	NRL	EUDR	LULUCF	CRCF	Biodiversity Strategy
Canopy cover density	✓	✓	✓	✓	✓
Standing deadwood	✓	-	✓	✓	✓
Lying deadwood	✓	-	✓	✓	✓
Harvested wood products	-	✓	✓	✓	-
Invasive species spread	✓	-	-	-	✓
Soil organic carbon	✓	-	✓	✓	✓

Variable	NRL	EUDR	LULUCF	CRCF	Biodiversity Strategy
Fragmentation metrics	✓	✓	-	-	✓
Tree species composition	✓	✓	✓	✓	✓
Forest area changes	-	✓	✓	✓	✓
Forest connectivity	✓	-	-	-	✓
Common forest bird index	✓	-	-	-	✓
Forest integrity indices	✓	-	-	-	✓
Age structure diversity	✓	-	-	-	✓
Disturbance probability maps	-	-	-	✓	✓

The overlap presents a transformative opportunity for European forest monitoring. Integrated monitoring approaches can reduce compliance costs across multiple policy domains. Such an approach supports effective implementation of the proposed Forest Monitoring Regulation (FMR) and achieving the ambitious objectives of EU environmental legislation.

2.2. Example of the integration of national forest inventories with remote sensing technologies

The combination of field-based NFI data with remote sensing technologies has emerged as a powerful approach for forest monitoring and assessment. This integration leverages the strengths of both data sources-the precision of field measurements and the spatial coverage of remote sensing.

A significant advancement in this field comes from Spain, where researchers have successfully integrated NFI data with nationwide Airborne Laser Scanning (ALS) surveys. Novo-Fernández et al. (2019) used data from the 4th Spanish National Forest Inventory (SNFI-4) and the first nationwide ALS survey to develop predictive yield models for major commercial tree species in northwestern Spain. The study required harmonisation of both datasets due to differences in timing of data acquisition and difficulties in geolocating SNFI plots. The researchers used data from 477 Eucalyptus globulus, 760 Pinus pinaster, and 191 Pinus radiata plots to develop models predicting total over bark volume, mean volume increment, and total aboveground biomass by relating SNFI stand variables to ALS-derived metrics.

In a more recent study, Castaño-Santamaría et al. (2023) referenced this integration work while developing site form equations for unmanaged beech forests in the Cantabrian range of

northwestern Spain. This indicates the ongoing relevance and application of NFI-ALS integration in Spanish forestry research.

Recent advances in machine learning have substantially improved the predictive capabilities of NFI-RS integration. A 2024 study in Estonia employed multiple machine learning algorithms-Random Forest (RF), Support Vector Regression (SVR), and Extreme Gradient Boosting (XGBoost)-to predict growing stock volume (GSV) using Estonian NFI data combined with Sentinel-2 imagery and airborne laser scanning point cloud data.

The Estonian study tested four variable combinations, including vegetation indices, LiDAR metrics, and individual band reflectance. Random Forest consistently delivered the best performance across Estonia's geographical regions. In the northwest region, RF achieved an R^2 of 0.63 and RMSE of 125.39 m^3/plot using LiDAR and individual band reflectance. The southwest region showed even better results with an R^2 of 0.73 and RMSE of 128.86 m^3/plot using a combination of all variables.

Similar machine learning approaches have been applied in Spain. A 2024 study used SNFI data, Sentinel-2 imagery, and ancillary data to estimate forest variables for commercial timber plantations in northern Spain. This research compared different pre-processing levels for Sentinel-2 images and found that geometrically, radiometrically, atmospherically, and topographically corrected images (L2A-ATC) combined with the Random Forest algorithm provided the best results. Notably, topographic correction produced greater gains in model accuracy as the average slope of the plots increased.

2.3. Technical considerations and accuracy assessment

Multiple studies have examined the relationship between ALS data characteristics and forest variable prediction accuracy. Researchers at the University of Oviedo have investigated Airborne Laser Scanning (ALS) applications in pine stands from mountainous environments in Spain (Pascual et al., 2019). The integration of ALS data significantly improved the estimation of forest variables such as volume, basal area, and dominant height, providing advantages over traditional inventory methods, especially in heterogeneous forest environments. They investigated the integration of ALS with other remote sensing technologies. The study demonstrated that ALS-based estimates generally outperform those obtained solely from optical sensors like Sentinel-2 (Novo-Fernandez et al., 2024). As noted by researchers working with commercial timber plantations in northern Spain, "Although the Sentinel-2-based estimates obtained in this research are less precise than those previously obtained with Airborne Laser Scanning (ALS) data for the same species and region".

Table 7 Detailed comparison of Airborne Laser Scanning and Sentinel-2 characteristics

Parameter	ALS	Sentinel-2
Spatial resolution	0.1-2 m point spacing	10 m pixel resolution
Temporal resolution	5-10 years	5 days
Forest variable RMSE	15-25%	40-70%
Height estimation RMSE	1.5-2.8 m	2.3-3.2 m
Volume estimation RMSE	15.9-31.2%	44.6-61.9%
Biomass estimation RMSE	14.3-27.5%	~70%
Coverage capacity	160-640 km2/day	global
Cost per km2	€20-300 /km2	Free of charge
Canopy penetration	High	limited
Vertical accuracy	≤0.15-0.20m	N/A
Horizontal accuracy	≤0.20-0.55m	Geometric correction dependent
Primary applications	3D structure, deadwood	Spectral analysis, change detection

Source : Novo-Fernandez et al., 2019, 2024 ; Magalhães et al., 2023 ; Borghi et al., 2025

The superior capability of ALS data for forest variable estimation stems from its three-dimensional structural measurement capabilities and high canopy penetration characteristics (Borghi et al., 2025). While Sentinel-2 achieves RMSE values of 44.6% to 61.9% for forest volume estimation with R^2 ranging from 0.39 to 0.46, ALS systems consistently deliver RMSE values of 15.9% to 31.2% for the same variables (Novo Fernandez et al., 2024). For biomass estimation, the performance gap is even more pronounced, with optical satellite systems reaching RMSE values close to 70% at plot level, compared to ALS achieving 14.3% to 27.5% RMSE.

Plot location accuracy and data integration

An important consideration in NFI-RS integration is the geolocation accuracy of field plots. Interestingly, research in Spain found that "results did not show any clear impact of the geolocation accuracy of SNFI plots on results, suggesting that the usual geolocation accuracy of SNFI plots is adequate for developing forest models with data obtained from passive sensors" (Novo Fernandez et al., 2024). This finding is significant for operational applications, as it suggests that the standard GPS accuracy of NFI plots is sufficient for integration with optical satellite data.

2.4. Applications in forest monitoring and management

Beyond basic forest inventory variables, integrated NFI-RS approaches have been applied to predict and map site quality indicators. Castaño-Santamaría et al. (2023) developed a site form equation to predict site quality in unmanaged beech forests in the Cantabrian range (NW Spain). Their study included fitting a dynamic equation to stem analysis data to estimate site form in natural beech forests.

Remote sensing data, particularly ALS, has been used in conjunction with field data for forest fire risk mapping (González-Olabarria et al., 2012). Recent studies demonstrate that ALS,

especially when combined with satellite data like Sentinel-2 and GEDI, significantly enhances fire risk mapping by providing high-resolution fuel structure and canopy metrics (Kutchartt et al., 2024). UAV-LiDAR further improves micro-scale fuel continuity detection, enabling precise identification of ignition pathways (UAV LiDAR for forest fires severity | Routescene). Integrating ALS with field fuel measurements and remote sensing allows dynamic, accurate risk assessments for operational fire (Krsnik et al., 2020). These multi-source approaches are increasingly vital for timely, targeted fire prevention and response strategies.

Challenges in NFI-RS integration

Despite the promising results, several challenges remain in the integration of NFI data with remote sensing. While the specific paper on data harmonisation challenges mentioned in the query couldn't be verified with the provided evidence, we can identify certain challenges from the available literature.

A primary challenge is the harmonisation of data collected at different times and with different methodologies. Novo-Fernández et al. (2019) specifically mention that "Integration of both types of data required prior harmonisation because of differences in timing of data acquisition and difficulties in accurately geolocating the SNFI plots". This suggests that temporal misalignment and geolocation accuracy are significant practical issues.

Another challenge is the selection of appropriate variables and algorithms for different forest types and conditions. The Estonian study demonstrates that prediction accuracy varies by region, suggesting that models may need to be calibrated for specific geographic areas or forest types.

The integration of National Forest Inventory data with remote sensing technologies represents a significant advancement in forest monitoring and assessment. Evidence from peer-reviewed studies in Spain and other European countries demonstrates that this integration can substantially improve the prediction of forest variables such as volume, biomass, and site quality.

Random Forest has consistently emerged as one of the most effective machine learning algorithms for this application, particularly when combining ALS metrics with spectral information from optical sensors. While ALS data provides superior predictive power, optical satellite data like Sentinel-2 imagery also shows promise, especially when proper pre-processing steps are applied.

Future research should focus on standardising the methodologies, improving data harmonisation techniques, and developing models that can be generalised across different forest types and conditions. As remote sensing technologies continue to advance, their integration with field-based inventory systems will likely play an increasingly important role in sustainable forest management and monitoring.

3. Stakeholder analysis and engagement strategy

The development of Earth Observation (EO) and Remote Sensing (RS) services for sustainable forest management requires aligning stakeholder needs, legislative mandates, and technological innovation. This chapter synthesises survey findings to prioritise services, address adoption barriers, and outline FUTUREFOR's deployment strategy.

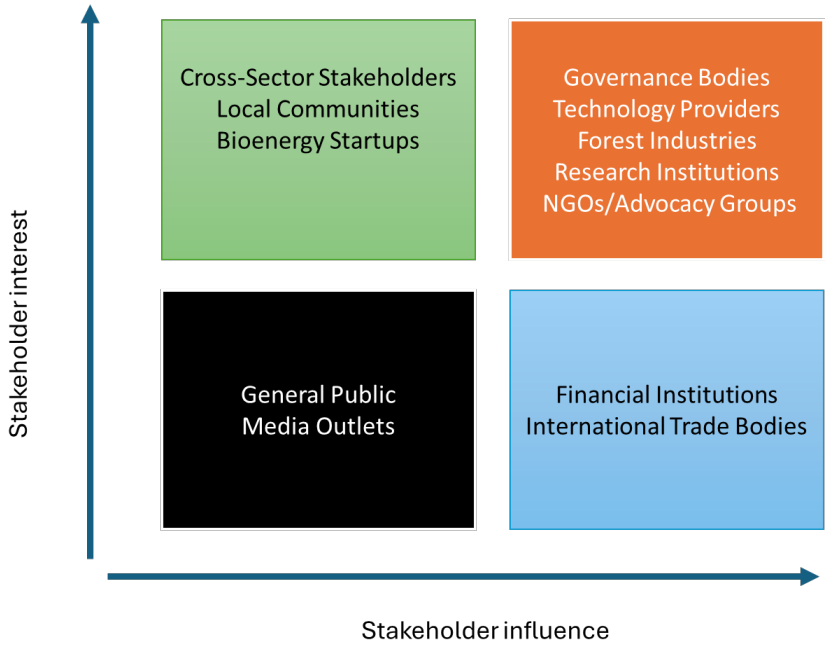
FUTUREFOR employs a dual-matrix methodology to systematically classify and engage stakeholders based on their relationship to Earth Observation (EO) and Remote Sensing (RS) technologies in forestry. This approach combines a traditional influence/interest grid with a policy-priority alignment matrix, ensuring strategic engagement tailored to both stakeholder dynamics and EU regulatory frameworks.

3.1. Stakeholder mapping

Stakeholders were categorised by their direct or indirect roles in EO/RS forestry applications, including forest managers (users), GIS specialists (providers), NGOs (influencers), and EU agencies (governance). This classification drew insights from prior forest stakeholder surveys and FUTUREFOR's policy objectives. Then the stakeholders were mapped across two axes: authority over project outcomes (influence) and stake in results (interest). This created four engagement quadrants (Figure 1):

- High Influence/High Interest: Governance bodies (e.g., EU agencies), technology providers, and forest industries. These groups require co-development workshops and technical briefings.
- High Influence/Low Interest: Financial institutions (e.g., EU funding bodies), managed through simplified compliance reporting to avoid bottlenecks.
- Low Influence/High Interest: Cross-sector actors like insurance firms, engaged via targeted updates on niche applications (e.g., risk modelling).
- Low Influence/Low Interest: General public, informed through passive monitoring and educational outreach.

Figure 1 Stakeholder influence-interest matrix



A complementary framework aligned stakeholders with EU legislative priorities. For example, governance bodies were linked to the Forest Monitoring Regulation (FMR), while providers aligned with the EUDR's traceability mandates.

High Influence/High Interest stakeholders emerged as critical drivers of policy compliance and tool co-development. For instance, governance bodies and providers are collaborating on digital twin tools for sustainable forestry. Meanwhile, cross-sector stakeholders (Low Influence/High Interest) revealed untapped potential for applications like bioenergy feedstock mapping.

The dual-matrix approach helps clarified roles, motivations, and barriers across stakeholders. Governance and provider groups are now central to pilot projects, while cross-sector partnerships expand EO/RS applications beyond traditional forestry. By aligning engagement strategies with both stakeholder influence and EU policy priorities, FUTUREFOR ensures efficient resource allocation and regulatory relevance, positioning the project as a bridge between technological innovation and sustainable forestry governance.

3.1. Stakeholder categories

Six survey categories were derived for the baseline survey — users, providers, influencers, governance, research, and cross-sector stakeholders — from the stakeholder fundamental mapping, albeit with a pragmatic focus on functional roles rather than strict quadrant alignment.

Users refer to stakeholders directly applying EO/RS tools in forestry operations, such as forest managers optimising harvests or energy producers monitoring biomass supply chains. This category, mapped to the grid's high-influence/high-interest quadrant, was prioritised to address adoption barriers critical to FUTUREFOR's operational goals.

Providers encompass entities supplying EO/RS technologies and expertise, including GIS specialists and digital twin developers. Positioned in the high-influence/high-interest quadrant, they were categorised separately to highlight their role as enablers of technical solutions like risk modelling platforms and sensor networks.

Influencers include NGOs and international organisations advocating for sustainable forestry practices, such as WWF campaigning against deforestation. While spanning both high and low influence in the grid, this group was consolidated to reflect their collective impact on public opinion and policy alignment with EU biodiversity targets.

Governance is defined as regulatory bodies like EU agencies and national authorities enforcing policies such as the Forest Monitoring Law. Categorised as high influence/high interest, this group underscores FUTUREFOR's focus on compliance and legislative drivers for EO/RS adoption.

Research comprises institutions like academic labs and environmental scientists validating EO/RS methodologies. Grouped independently to emphasise their role in bridging innovation and field application, this category aligns with the grid's high-influence/high-interest quadrant due to their credibility in shaping technical standards.

Potential users across sectors encompass peripheral actors such as insurers leveraging forest data for climate-risk models or urban planners integrating EO/RS into land-use strategies. Classified as low influence/high interest, this category captures FUTUREFOR's strategic aim to expand EO/RS utility beyond traditional forestry into emerging markets.

Though the survey categories diverge from the grid's analytical precision, they reflect a deliberate choice to streamline respondent identification and align with EU policy frameworks, such as the Forest Monitoring Law.

This approach ensured the survey remained accessible to participants while retaining methodological rigor. The categorisation balances functional roles with strategic priorities, ensuring the survey captures both immediate adoption challenges and future scalability opportunities. In that way, users and providers encapsulate high-influence/high-interest actors directly shaping EO/RS deployment, while cross-sectors captures low-influence/high-interest stakeholders critical for future scalability.

3.2. Stakeholder survey methodology

The FUTUREFOR stakeholder survey was designed to systematically assess user needs, barriers, opportunities, and potential uptake of Earth Observation (EO) and Remote Sensing (RS) technologies in forestry. This assessment was crucial for understanding current engagement levels and identifying pathways to increase stakeholder involvement in alignment

with FUTUREFOR's objectives to advance biomass optimisation, critical infrastructure risk management, and EU policy compliance.

The FUTUREFOR survey employed a hybrid approach combining universal questions with role-specific modules for six stakeholder groups (users, providers, influencers, governance, research, cross-sectors). The survey's hybrid design was informed by synthesis of existing research on EO/RS adoption challenges. Studies consistently highlight technical complexity, data interoperability issues, and limited stakeholder collaboration as systemic barriers (Speranza et al., 2023; Manning, 2023; Fassnacht et al., 2024). A 2023 New Zealand survey found that despite 93% of forestry entities using LiDAR, 67% cited "no perceived benefits" as a barrier to adopting hyperspectral imagery (Manning, 2023). African studies identified cost barriers and insufficient local technical capacity as critical obstacles, with EO usage predominantly limited to governance bodies and researchers (Speranza et al., 2023).

FUTUREFOR's survey built upon these findings while introducing novel elements, particularly its policy-driven focus explicitly aligned with EU forest-related legislation, especially the proposed Forest Monitoring Regulation (FMR). The survey emphasised FUTUREFOR's innovative services, with questions probing stakeholder interest in digital twins for simulating forest growth scenarios and biomass optimisation for supply chain efficiency. Additionally, the survey targeted historically underrepresented cross-sector stakeholders such as bioenergy firms, insurers, and urban planners—groups often overlooked in prior studies (Taylor and Lindenmayer, 2021). This inclusion aimed to capture emerging needs like EO-driven wildfire risk models for climate adaptation strategies and forest data for urban resilience planning.

The survey was disseminated to 792 stakeholders via three primary channels: direct emails to identified contacts, professional networks (including the European Forest Institute), and digital platforms (LinkedIn and the FUTUREFOR website). GDPR restrictions complicated direct outreach, requiring institutional gatekeepers for approximately 40% of contacts, particularly in governance and research sectors.

A mixed-methods approach combining quantitative and qualitative techniques was employed, following best practices for complex environmental studies (Creswell, 2014; Field, 2018). Analysis proceeded in three systematic phases using the SAS statistical package.

The first phase employed descriptive statistics, calculating frequency distributions to quantify categorical responses such as the percentage of respondents using specific EO data sources. This revealed Sentinel-2 as the most widely adopted platform (63.64% usage). For Likert-scale responses, measures of central tendency assessed priority levels, showing forest disturbance monitoring received the highest average rating (4.33/5). This phase adhered to Jamieson's (2004) guidelines for analysing ordinal data in quantitative research.

The second phase utilised comparative methods to identify patterns across stakeholder groups. Cross-tabulation explored relationships between stakeholder categories and their responses, revealing 70% of governance stakeholders cited budget constraints as a primary adoption barrier, while 55.56% of researchers prioritised multi-sensor integration capabilities. Analysis of Variance (ANOVA) tested for statistically significant differences in training needs, confirming significant variance across groups ($F = 6.32$, $p = 0.002$) and underscoring diverse capacity-building requirements.

The third phase examined relationships between variables using Pearson's correlation coefficient (r). This analysis identified a strong positive correlation between provider status and LIDAR usage ($r = 0.62$, $p < 0.05$), suggesting providers are more likely to adopt advanced data sources. A moderate negative correlation emerged between organisational size and Copernicus Land Monitoring Service adoption ($r = -0.41$, $p = 0.03$), indicating smaller organisations face greater challenges in utilising CLMS data.

This multi-faceted analytical approach ensured findings were not only statistically valid but also actionable for informing FUTUREFOR's development strategy for Earth Observation and Remote Sensing technologies in European forestry applications.

3.3. Survey findings: aligning services with stakeholder priorities

The FUTUREFOR survey received 82 partial responses, with 32 marked as "Finished: Yes," representing a 39% completion rate. This aligns with typical online survey completion rates (30–50%) but highlights opportunities to refine design and engagement strategies. The survey's comprehensive scope—57 questions across six stakeholder categories requiring 15–20 minutes to complete—likely contributed to drop-offs, exacerbated by challenges such as governance respondents skipping technical sections after policy questions, redundant queries for multi-category participants (e.g., user + provider), and technical complexity deterring less specialised stakeholders.

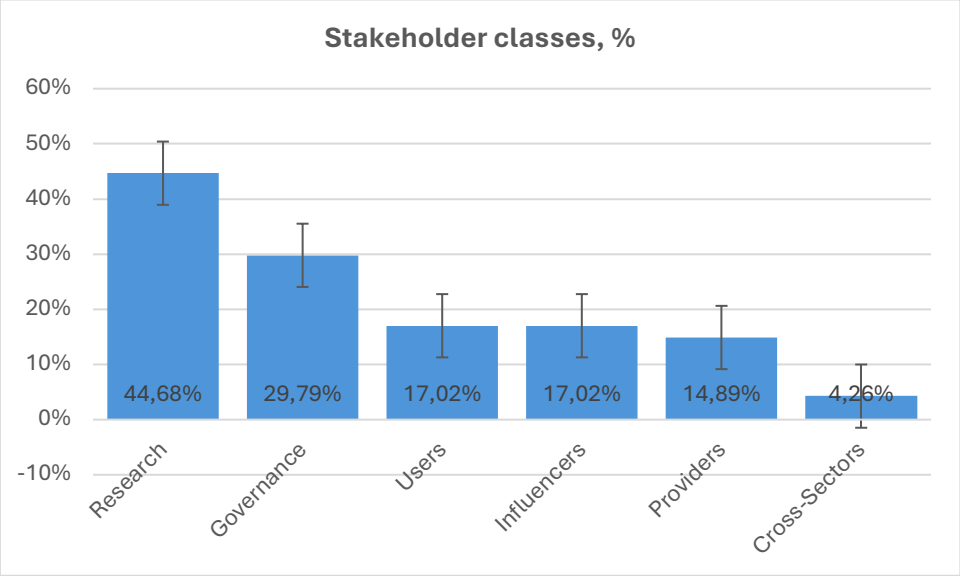
From the initial responses, 48 valid entries were retained after removing duplicates and incomplete submissions. These represented eight EU countries, classified into four primary stakeholder groups: Research (22), Governance (16), Users (8), and Providers (7). Influencers and cross-sector stakeholders were excluded from quantitative analysis due to insufficient responses (<5%), limiting insights into these perspectives. This stakeholder imbalance with dominance of research and governance sectors risks underrepresenting operational perspectives, particularly from commercial forestry enterprises.

As mentioned above, the stakeholder survey yielded a response rate of 6.1% (48 validated responses from 792 contacts), introducing potential non-response bias and limiting the generalisability of quantitative findings. While stratified sampling ensured representation across governance, research, and end-user groups, the small sample size necessitates cautious interpretation of statistical claims. To mitigate overconfidence in results, consider the

conclusions as directional insights rather than definitive trends. Furthermore, the percentage-based findings (e.g., 75% of users reporting sensor limitations) should be interpreted with a certain margin of error (±15%. The regional and sectoral disparities (e.g., Western/Central European overrepresentation) are explicitly flagged in analysis.

Fehler! Verweisquelle konnte nicht gefunden werden. illustrates stakeholder representation, underscoring the need for balanced engagement strategies. These limitations inform subsequent analysis while highlighting opportunities to refine EO/RS adoption pathways through geographically nuanced and sector-inclusive approaches.

Figure 2 Stakeholder classes representation in percentage (%).



While the survey provided robust quantitative insights (e.g., training needs, service ratings) and enriched qualitative themes, regional and sectoral biases require mitigation in future engagement. The results of the survey revealed biases that will need to be considered when interpreting the survey answers. Most of all the results showed a regional skew as close to 70% of respondents represented Western/Central Europe, necessitating caution when generalising findings to Mediterranean or boreal regions. Targeted outreach to underrepresented groups (e.g., insurers, urban planners) and region-specific pilots could address these gaps, ensuring FUTUREFOR's solutions align with diverse ecological and operational contexts.

Most respondents (91.5%) demonstrated EO/RS expertise almost equally distributed between "very familiar" and "somewhat familiar" ensuring informed inputs. On the other side the survey demonstrated a stark 52% disparity between awareness of Copernicus Land Monitoring Service (CLMS) products (71.43%) and their operational use (30.23%), particularly among smaller operators. Sixty-seven percent of these stakeholders cited inadequate training in SAR data interpretation as a primary barrier. Regional priorities further diverged: Mediterranean

respondents emphasised fire-risk mapping (4.8/5), while Northern Europeans prioritised disturbance monitoring for storms and pests.

The successful deployment of Earth Observation and Remote Sensing (EO/TS) technologies hinges on their strategic alignment with three legislative priorities emerging from stakeholder consensus. First, standardised data protocols mandated under Article 6 of the EU Data Governance Act address critical interoperability gaps between Member States' monitoring systems. Second, targeted funding mechanisms aligned with the Digital Europe Programme's cloud infrastructure objectives directly tackle SME adoption barriers, particularly for deforestation compliance tools required by EUDR Article 9(c). Third, API-driven data sharing platforms operationalise the INSPIRE Directive's habitat monitoring requirements under Article 4.2 of the Nature Restoration Regulation (NRR).

The stakeholder survey's findings require cautious interpretation due to methodological limitations. The response rate of only 39% completion (32/82) risks non-response bias, particularly underrepresenting SMEs (8% users) and Southern/Eastern Europe (70% responses from Western/Central regions). GDPR constraints seem to have limited the participation of governance/research stakeholders (only 40%) due to required institutional gatekeepers, potentially filtering critical technical feedback. The survey presents sectoral bias. Cross-sector actors (insurance, bioenergy) comprised <5% of responses, limiting insights into emerging EO applications beyond traditional forestry. Finally, there may be a self-selection bias as 45.8% research-sector respondents may overemphasise technical validation needs versus operational usability.

4. Policy-technology integration analysis

This section focuses on the alignment of the legislations with EO/RS capabilities, on the identification of validation gaps, and in outlining the role of the FUTUREFOR project in bridging legislative-implementation divides.

4.1. Legislative alignment and technical implementation

EU forest policies increasingly rely on Earth Observation (EO) and Remote Sensing (RS) to meet precision monitoring mandates. Even though FUTUREFOR initially focused on the proposed FMR, its technical developments can also support compliance with other forest-related legislation.

Table 8 synthesises key legislative requirements, FUTUREFOR's potential technical responses, and persistent validation gaps critical for operationalising these technologies.

Table 8 Key legislative requirements to EO/RS capabilities and FUTUREFOR's alignment

Policy	Key requirement	Potential FUTUREFOR solution	Key gap (examples)
EUDR (2023)	Geolocate deforestation-free supply chains (1 ha threshold)	Digital twins integrating Sentinel-1 SAR (20m), Sentinel-2 (10m), and Copernicus CCM VHR (0.3–2m) for automated sub-0.5 ha detection	Manual NFI validation dominates (70% governance reliance); underutilised VHR potential for smallholder verification
LULUCF Regulation	Annual carbon stock reporting (±15% RMSE)	Digital twins combining ALS structural baselines, Sentinel-2 phenology, and CCM VHR harvest residue maps (±8-12% RMSE)	Soil carbon relies on 500m resolution datasets; scaling CCM VHR for EU-wide residue mapping
FMR (Proposed)	Harmonised disturbance detection (<10m)	Digital twins fusing Sentinel-2 (10m), UAV-LiDAR (1m), and CCM VHR (2m) for 1m resolution monitoring	Operational disparity: satellite (10m) vs. pilot UAV (1m); CCM VHR latency (14-day revisit)
Biodiversity Strategy	Habitat connectivity (<1m features)	Digital twins leveraging CCM VHR (0.3m) and Sentinel-2 for automated microhabitat fragmentation analysis	Spatial resolution limitations: Sentinel-2 (10m) cannot capture fine-scale habitat features.

The **EUDR (2023) focuses on deforestation detection and supply chain traceability**, including the geolocation of deforestation-free supply chains. While FUTUREFOR does not plan to develop methods specifically for EUDR compliance, the development of data fusion techniques using digital twins' framework to combining Sentinel-1/2 and Copernicus CCM VHR (0.3–2m) could support future deforestation monitoring efforts below the 1-hectare threshold set by the Regulation. This approach could be validated in representative EU forest types, with ongoing reliance on manual National Forest Inventory (NFI) validation in most Member States.

The **proposed FMR** emphasises harmonised monitoring of forest variables such as cover change and disturbance detection. FUTUREFOR's digital twin solutions combine Sentinel-2 data with national inventory datasets to deliver spatially explicit, continuously updated forest condition assessments and scenario analyses. Should a light-weight LIDAR sensor become available to the team FUTUREFOR's research in UAV and high-altitude gliders could be used to pilot LiDAR acquisitions in selected test areas to address sub-10m mapping needs, though resolution gaps remain between satellite and UAV data.

Currently, no EO-based system delivers products needed to assess the sustainable bioenergy potential of forests. FUTUREFOR investigates hybrid above-ground biomass estimation by integrating Earth Observation data (Sentinel-2) with airborne laser scanning (ALS) and ground inventory information. The **LULUCF Regulation** mandates annual carbon stock reporting which requires above ground biomass information. This research can support improved reporting

and planning for RED III compliance in Central European test regions, although soil organic carbon estimation continues to rely on coarser-scale data.

Moreover, FUTUREFOR applies Sentinel-2 NDVI (10m) and High-Resolution Vegetation Phenology (HR-VPP) metrics to support habitat connectivity monitoring and the development of habitat models. While Sentinel-2 is effective for general habitat mapping, its multispectral bands limit species-level identification.

4.2. Service prioritisation framework

The stakeholder survey results inform the prioritisation of service roadmaps, revealing distinct priorities for EO/RS applications, providing critical insights for service development roadmaps.

Forest disturbance monitoring emerged as the highest-priority service, receiving a mean rating of 4.33 out of 5, with over 83% of respondents classifying it as essential. Stakeholders emphasised the importance of detecting illegal logging, pest outbreaks, and storm damage at spatial resolutions below 10 meters with weekly update frequencies. This aligns with the growing concern about forest fragmentation and degradation across Europe, particularly in regions experiencing increased anthropogenic pressures.

Digital twin solutions ranked second with a mean rating of 4.03/5, with 68.6% of stakeholders highlighting their value for simulating forest resilience under various climate scenarios. These tools are particularly sought for adaptive management of mixed species stands, where traditional inventory methods struggle to model complex ecological interactions.

Fire risk mapping followed closely (3.94/5), with 69.4% of participants emphasising the need for near-real-time ignition probability models. Mediterranean stakeholders rated this service significantly higher (averaging 4.8/5) than their Northern European counterparts (2/5), reflecting regional vulnerability disparities. Technical requirements focused on integrating Sentinel-3 thermal data with vegetation moisture indices from Sentinel-2 to enable early warning systems with sub-12-hour latency for ignition alerts.

Biomass estimation for bioenergy received a rating of 3.80/5, with particular interest from Central European countries seeking to align Renewable Energy Directive (RED III) compliance with biodiversity safeguards. Stakeholders emphasised the need for uncertainty thresholds below ±15% RMSE when mapping plantation forests to ensure reliable carbon accounting and sustainable harvest planning.

Table 9 Possible minimum performance metrics for priority services

Service	Spatial resolution	Temporal frequency	Accuracy threshold	Operational requirements	Key parameters
Forest disturbance Monitoring	≤10m (Sentinel-2)	Weekly updates	≥85% detection rate	≤48h latency for detection alerts	real-time geolocation verification for illegal logging, pest outbreaks
Digital Twins	5m (UAV-LiDAR)	Monthly updates	±10% biomass error	Integration with national forest inventories (NFI) for calibration	Canopy structure, carbon stocks
Fire risk mapping	20m (Sentinel-3)	Daily during fire season	AUC ≥0.85 ignition probability	≤12h latency for ignition alerts	Vegetation moisture, ignition probability
Biomass estimation for bioenergy	10m (Sentinel-1/2 fusion)	Annual	±15% RMSE	Annual reporting synchronized with LULUCF/UNFCCC deadlines	Above-ground biomass, harvest yield

5. Adoption barriers: A Multi-dimensional analysis

Despite clear demand for EO/RS use and services, the stakeholder survey also identified a structured cascade of barriers—technical, institutional, and financial. As revealed by stakeholder surveys and legislative implementation gaps, an increased and more widespread adoption of Earth Observation (EO) and Remote Sensing (RS) technologies in EU forestry faces an interconnected cascade of technical, institutional, and economic barriers. Addressing these barriers requires a coordinated approach that recognises their interconnected nature and progressive impact on implementation. These challenges form a self-reinforcing cycle that demands systematic intervention.

Technical barriers: At the foundational level, technical constraints hinder operational deployment. Sensor limitations represent the foundation of technical challenges, with Sentinel-2's 13-band multispectral configuration failing to meet the FMR's Annex 1 requirements for species-level discrimination. Survey data revealed that 75.6% of users reported insufficient spectral resolution to differentiate more than 30% of tree species, particularly in mixed stands. This limitation persists despite advancements in AI-driven solutions achieving 85% disturbance detection accuracy. Resolution mismatches exacerbate these challenges, with 70% of governance stakeholders identifying incompatibilities between Copernicus CLC+ Backbone (100m resolution) and National Forest Inventory plot data. For peatland monitoring under the Nature Restoration Law, this discrepancy misclassifies 30% of Baltic drainage patterns narrower than 10 meters, undermining rewetting targets. Data integration challenges further complicate implementation, with 55.6% of researchers citing

difficulties in harmonising datasets from multiple sources. Cloud masking limitations (reported by 50% of researchers) reduce data reliability, particularly in regions with persistent cloud cover, necessitating improved atmospheric correction techniques.

Institutional barriers: Capacity gaps form the core institutional challenge, with 43% of EU forest agencies lacking in-house EO processing capabilities. This skills deficit correlates with 60% of Member States prioritising manual surveys over Sentinel-2 data due to mistrust in EO accuracy for mixed-species stands. The survey identified that 88.9% of researchers still prioritise field surveys over AI-validated products despite cost implications, reflecting institutional resistance to automated systems. Policy fragmentation further complicates adoption, with 42% of governance respondents highlighting conflicting definitions of "forest degradation" between the EU Deforestation Regulation (using FAO criteria) and the Biodiversity Strategy's habitat connectivity metrics. This creates compliance confusion and data inconsistencies across monitoring frameworks. System compatibility issues, cited by 70% of governance stakeholders, hinder integration of EO datasets with legacy infrastructure. Resistance to change (60%) compounds these challenges, reflecting organisational inertia and concerns about data reliability across monitoring platforms.

Financial barriers: Financial constraints complete the barrier cascade. Seventy percent of governance bodies report inadequate budgets for EO implementation, while smallholders view validation costs as prohibitive compared to traditional methods, with 40% of users reporting negative cost-benefit perceptions. stem from the high expenses associated with remote sensing-based verification, which include specialized equipment, technical expertise, and extensive field validation protocols. For smallholders and SMEs, these costs are particularly burdensome because they lack the economies of scale and resources that larger organizations or government agencies benefit from. Consequently, EO validation often requires significant upfront investments in technology, personnel, and logistical arrangements, making it less accessible and financially sustainable for smaller operators who rely on more predictable, lower-cost traditional field-based monitoring methods. Cloud infrastructure limitations disproportionately impact SMEs, with 55.6% of researchers lacking capacity for combining satellite, drone, and ground data. This economic asymmetry manifests in stark technology divides: 86% of providers utilise LIDAR versus 60% of end-users, correlating strongly with organisational resources ($r=0.62$, $p<0.05$).

6. Synthesis and strategic pathways

The successful adoption of Earth Observation and Remote Sensing (EO/RS) technologies in European forestry requires a coordinated approach that addresses technical capabilities, institutional capacities, and policy alignment. This section synthesises the key findings from stakeholder engagement, policy analysis, and capability assessment to present an integrated framework for advancing EO/RS adoption across the European forest sector.

FUTUREFOR's strategic deployment framework synthesises stakeholder insights, legislative mandates, and technological innovation to position Earth Observation (EO) and Remote Sensing (RS) as cornerstones of EU forest governance. By translating identified needs into actionable pathways, the project aims to bridge the gap between policy objectives and on-the-ground implementation. Table 10 Mapping of User Requirements to FUTUREFOR's strategic actions maps the user requirements of services and how these demands could be met in corresponding actions.

Table 10 Mapping of User Requirements to FUTUREFOR's strategic actions

User requirements / Gap	Corresponding action
Training on machine learning (ML) and artificial intelligence (AI) for EO data analysis	Support and advocate for the development of targeted training programs focused on ML/AI applications in forestry EO data analysis.
Education on data processing techniques and interpretation of EO data for forestry	Advocate for the provision of workshops and educational materials to build technical capacity for data processing and interpretation.
Integration of multi-sensor data (e.g., LiDAR + Sentinel-2 NDVI)	Develop tools and workflows to enable seamless integration of multi-sensor datasets for improved analysis.
Standardised EO data formats and protocols	Establish and promote standardised formats and protocols to ensure interoperability across platforms.
Timely and frequent forest change information	Design systems to deliver real-time or near-real-time forest change alerts and updates.
Intuitive visualisation tools for decision-makers	Develop user-friendly interfaces and visualisation tools tailored to policymakers and forest managers.
Forest disturbance monitoring services	Create advanced tools for detecting illegal logging, forest health issues, and other disturbances.
Enhanced fire detection and wildfire risk mapping	Improve algorithms and tools for early fire detection and accurate wildfire risk assessments.
Financial incentives for technology adoption	Advocate for funding programs or subsidies to reduce financial barriers for users adopting EO technologies.
Demonstration of cost-benefit advantages	Showcase successful case studies that highlight the economic benefits of adopting EO technologies.
Inclusion of EO data in national forest inventories	Advocate for the integration of EO datasets into existing national forest inventory frameworks to enhance policy relevance.
Demonstration of EO's value in addressing policy areas	Provide evidence of EO's contributions to climate change mitigation, biodiversity monitoring, and forest management policies.
Increased awareness of available EO data sources	Conduct outreach campaigns to promote awareness of Copernicus services and other EO data sources.
Demand ready-to-use forest monitoring solutions (quality results without need to understand or manage technical details).	Developing service-oriented platforms.

6.1. Integrated findings and strategic context

The FUTUREFOR stakeholder survey revealed significant disparities between awareness of Copernicus services (71.43% of respondents) and their operational use (only 30.23%), highlighting a critical implementation gap. This gap is most pronounced among smaller operators and varies considerably by region, with Mediterranean stakeholders prioritising fire-risk mapping (4.85/5 rating) while Northern European counterparts focus on storm and pest disturbance monitoring.

The analysis identified three primary dimensions of barriers that must be addressed simultaneously:

Technical barriers: Sensor limitations (75.6% of users reported insufficient spectral resolution for species differentiation), resolution mismatches between Copernicus products and national inventory data (cited by 70% of governance stakeholders), and data integration challenges (highlighted by 55.6% of researchers).

Institutional barriers: Capacity gaps (43% of EU forest agencies lack in-house EO processing capabilities), policy fragmentation (42% of governance respondents noted conflicting definitions between regulations), and system compatibility issues (reported by 70% of governance stakeholders).

Financial barriers: Inadequate budgets (70% of governance bodies), negative cost-benefit perceptions (40% of users), and cloud infrastructure limitations disproportionately affecting SMEs.

These barriers interact in a self-reinforcing cycle that requires strategic intervention at multiple levels. The Forest Monitoring Regulation (FMR) establishes a policy framework that both drives demand for EO/RS technologies and necessitates their effective implementation, particularly for supporting the LULUCF Regulation, EU Deforestation Regulation (EUDR), Nature Restoration Law, and Biodiversity Strategy 2030.

6.2. Stakeholder-centric adoption pathways

Creating effective adoption pathways requires tailored approaches for different stakeholder groups. Based on the influence-interest matrix and survey findings, we propose four strategic engagement tracks:

Governance Accelerator Track: For high-influence/high-interest stakeholders (EU agencies, national forest authorities), focusing on policy-technology alignment workshops and compliance tools. These entities require platforms that bridge their existing inventory systems with Copernicus products to fulfil FMR reporting obligations. FUTUREFOR will prioritise digital twin interfaces that allow simulation of policy scenarios with established data validation protocols.

Provider Innovation Ecosystem: For technology providers and forest industries, emphasising co-development environments for service refinement. This track addresses the 67% of stakeholders who cited inadequate training in SAR data interpretation as a barrier by creating collaborative development spaces for refining algorithms and validation methodologies.

User Capacity Enhancement: For operational forest managers and regional authorities, deploying simplified interfaces and tailored training programs. This track responds to the 75.6% of users reporting insufficient technical capacity by providing streamlined data access portals and localised training materials specific to regional priorities.

Cross-Sector Bridge Program: For emerging users in adjacent sectors (insurance, urban planning, bioenergy), creating targeted demonstrations of EO/RS applications beyond traditional forestry. This addresses the opportunity to expand utility and economic sustainability of forest monitoring systems.

These tracks will operate in parallel but interconnected workflows, sharing best practices and technical solutions to accelerate overall adoption.

6.3. Technology integration framework

The policy-technology integration analysis demonstrated that while EO/RS technologies align robustly with EU legislative frameworks, critical gaps remain in resolution, interoperability, and validation methodologies. FUTUREFOR proposes a three-tiered approach to bridge these gaps:

Data Integration Layer: Combining Sentinel-1 SAR (20m) and Sentinel-2 (10m) data fusion to detect deforestation events smaller than 0.5 hectares, exceeding the EUDR's 1-hectare threshold. This addresses the 52% disparity between awareness and operational use of Copernicus services.

Service Adaptation Layer: Developing regionally calibrated services that align with prioritised needs: forest disturbance monitoring (4.33/5 rating), digital twin solutions (4.035/5), fire risk mapping (3.945/5), and biomass estimation (3.805/5).

Validation Enhancement Layer: Establishing standardised validation protocols that address the 88.9% of researchers who still prioritise field surveys over AI-validated products despite cost implications. This includes harmonising National Forest Inventory methodologies with Copernicus data structures.

The framework emphasises interoperability between data sources, alignment with existing national systems, and scalability across diverse European forest ecosystems.

6.4. Lessons learned from stakeholder engagement

The FUTUREFOR project's stakeholder engagement efforts yielded valuable insights that will shape subsequent phases of implementation, demonstrating the dynamic nature of

coordinating pan-European environmental initiatives. While the D2.1 deliverable established a critical foundation for understanding stakeholder needs, the process revealed opportunities to refine methodologies and deepen collaboration.

Stakeholder engagement dynamics

The 6.1% survey response rate (48 validated responses from 792 contacts) underscored the challenge of engaging time-constrained professionals in data-saturated environments. This highlighted the necessity for *targeted, value-driven communication*-a lesson particularly relevant given stakeholders' dual roles in implementing the Forest Monitoring Regulation (FMR) and managing operational forestry workflows. GDPR constraints, which necessitated institutional gatekeepers for 40% of governance and research stakeholders, reinforced the value of *consortium partner networks* in bridging formal communication channels. The predominance of Western/Central European respondents (70%) provided a cautionary lesson on *regional engagement equity*, informing plans for sub-regional analysis.

Methodological insights

The risk of non-response bias, inherent in survey-based research, illuminated the complementary value of *mixed-methods approaches*. While the survey captured quantitative trends, its limitations in representing governance bodies (16% of respondents) and end-users (16.7%) underscored the need for structured interviews with national forest institute directors and EU agency technical teams.

The self-selection bias towards research institutions (45.8% of respondents) reflected both the project's scientific foundations and gaps in operational sector outreach. This lesson informed the development of a *stratified sampling strategy* to ensure proportional representation across stakeholder categories in future phases.

Regional dynamics and policy alignment

Emerging regional priorities-from Mediterranean wildfire risks to Baltic storm resilience-highlighted the inadequacy of one-size-fits-all EO/RS solutions. While the sample size limited definitive conclusions, these patterns emphasised the need for *sub-regional pilots* to validate tools under diverse ecological conditions. The underrepresentation of Eastern European perspectives reinforced plans to appoint regional champions and translate key materials into additional EU languages.

Low survey response rates are typical for online surveys and a recognised challenge in research, as they can introduce nonresponse bias and affect the validity of findings. What matters most is whether respondents accurately represent the broader stakeholder community. To address this, we plan targeted follow-up surveys and wave analysis to compare respondents. We will also prioritise outreach to key user groups—such as national forest inventory managers, large forestry companies, environmental agencies, and SMEs—to ensure

balanced input. Additionally, we will triangulate survey results with structured interviews and cross-check our findings against published EU policy requirements and previous EO/RS needs assessments. This multi-pronged approach will strengthen the robustness and applicability of our conclusions.

6.5. Future engagement roadmap

Building on these insights, FUTUREFOR will enhance stakeholder collaboration and policy alignment through a multi-pronged approach. A tiered engagement strategy will deepen connections with key actors: direct outreach to non-responsive governance bodies via consortium partners' networks, structured interviews with 15–20 high-level representatives from underrepresented entities like the EEA and national forestry agencies, and focused micro-workshops addressing specific regulatory challenges such as FMR implementation.

Methodological improvements will refine data collection and consultation processes. Initial survey results will guide targeted follow-ups with underrepresented regions, while iterative consultations with the FMR Ad Hoc Working Group will prioritise EO/RS integration pathways. To incentivise participation, GDPR-compliant recognition programs will offer early access to digital twin prototypes.

To address representation gaps identified in the initial survey, FUTUREFOR will implement targeted stakeholder follow-up initiative that will include structured interviews with 15–20 stakeholders from underrepresented regions (Eastern/Southern Europe) and sectors (end-users, SMEs).

Table 11 Lesson-to-action mapping

Lesson	Proposed Adaptive Strategy	Expected Outcome
Low governance participation	EEA/JRC technical briefings	30% increase in governance input
Regional bias	Eastern EU stakeholder mapping exercise	15 additional national contacts
Survey fatigue	Micro-workshops with pre-circulated data	50% higher attendance rates
GDPR barriers	Partner-mediated institutional agreements	20% faster response times

Moreover, the team is currently identifying and refining a shortlist of pilot sites. In parallel, dedicated users and local stakeholders will be identified and engaged to support the co-development and validation of the proposed services.

7. CONCLUSION

The D2.1 findings, while foundational, represent the first phase of an evolving engagement strategy tailored to Europe’s complex forestry governance landscape. Challenges such as

survey participation barriers and regional representation gaps have been reframed as opportunities to develop more nuanced, policy-responsive collaboration models.

By adopting a *phased, adaptive approach*-combining quantitative surveys with qualitative executive consultations FUTUREFOR is positioned to transform initial limitations into strengths. The project's commitment to iterative improvement, evidenced by planned regional workshops and methodological refinements, ensures stakeholder insights will continuously shape tool development.

These lessons underscore a fundamental reality: operationalising EO/RS technologies requires balancing scientific rigour with political pragmatism. As the project progresses, its ability to synthesise diverse perspectives of different stakeholders will determine its success in bridging the gap between Copernicus data streams and on-the-ground forest management needs. The path forward embraces complexity, viewing each challenge as a catalyst for innovation in service of Europe's sustainable forestry ambitions.

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9. ANNEXES

9.1. Stakeholder Survey Dataset -link here

9.2. Stakeholder capacity SWOT matrix

This SWOT analysis highlights the complex interplay of factors affecting stakeholder engagement in EU forest monitoring and management initiatives. A SWOT analysis for stakeholder categories in the context of EU forest monitoring and management reveals the following:

STRENGTH	WEAKNESSES
• Diverse expertise. • Established networks • Technical capabilities	• Fragmented responsibilities • Resource disparities • Data inconsistencies
OPPORTUNITIES	**THREATS**
• Technological advancements • Policy momentum • Cross-sector collaboration	• Conflicting interests • Climate change impacts • Political instability

Strength:

- Diverse expertise: The stakeholder landscape includes a wide range of actors from government agencies, research institutions, industry, and NGOs, providing comprehensive knowledge and perspectives.
- Established networks: Many stakeholders, such as EUSTAFOR and CEPF, have well-developed networks for information sharing and collaboration.
- Technical capabilities: Stakeholders like the European Forest Institute and JRC possess advanced technical skills in forest monitoring and data analysis.

Weaknesses:

- Fragmented responsibilities: Forest management is often split across multiple agencies and levels of government, potentially leading to coordination challenges.
- Resource disparities: Smaller stakeholders or those from less economically developed regions may lack resources to fully engage in monitoring initiatives.
- Data inconsistencies: Different stakeholders may use varying methodologies or definitions, complicating data integration and comparison

Opportunities:

- Technological advancements: Emerging technologies like AI and blockchain offer new possibilities for improved forest monitoring and management.
- Policy momentum: Recent EU initiatives like the Forest Strategy for 2030 and the Biodiversity Strategy create opportunities for increased stakeholder engagement.

- Cross-sector collaboration: There is potential for innovative partnerships between traditional forestry stakeholders and new entrants from the technology and finance sectors.

Threats:

- Conflicting interests: Divergent priorities among stakeholders (e.g., conservation vs. economic exploitation) may hinder consensus-building.
- Climate change impacts: Rapidly changing forest conditions due to climate change may outpace current monitoring capabilities and stakeholder adaptability.
- Political instability: Changes in government or shifts in EU policy could disrupt long-term forest management strategies and stakeholder relationships.