FORTRACK

Tracking Interactions of Tree Mortality, Functional Diversity, and Ecosystem Responses to Climate Stressors with Earth Observation

Science Requirements Document (Deliverable D1.1)

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1 Purpose, Scope, and Role of this Document

1.1 Role of the Science Requirements Document within FORTRACK

This document constitutes Deliverable D1.1 of the FORTRACK project and fulfils the objectives of Task 1 (Science Requirements Analysis) as defined in the Statement of Work. Its primary purpose is to define the scientific and methodological requirements necessary to address the FORTRACK research objectives at the interface of climate change, tree mortality, biodiversity, and ecosystem functioning.

The Science Requirements Document (SRD) establishes a shared and explicit understanding of the scientific challenges to be addressed, the knowledge gaps targeted, and the analytical capabilities that must be enabled by the project. The SRD serves as a foundational reference for all subsequent project activities, ensuring coherence between scientific objectives, data usage, methodological development, and expected outputs, while remaining aligned with the goals of ESA's Climate Change Initiative and the ESA EO Science Strategy.

An updated version of this document (D1.1 v2) will be produced at month 12 to incorporate feedback from initial implementation activities and, where applicable, stakeholder consultations, ensuring continued alignment between scientific objectives and project execution.

1.2 Relationship to Technical Implementation Tasks

This document defines *what* scientific and methodological capabilities are required within FORTRACK, but deliberately does not prescribe *how* these capabilities are to be technically implemented. It therefore occupies a boundary position between scientific problem definition (Task 1) and technical and analytical implementation (Tasks 2–4).

The requirements specified here provide the guiding framework for:

- the development and tailoring of datasets, tools, and model–data integration efforts in Task 2,
- the execution of the main scientific analyses in Task 3, and
- the evaluation, synthesis, and roadmap activities in Task 4.

Detailed descriptions of algorithms, software architectures, and operational workflows are intentionally deferred to subsequent deliverables, including the Technical Note on data tailoring (D2.1), the project repository and user documentation (D2.2–D2.3), and the scientific publications and evaluation reports.

2 Scientific Context, State of the Art, and Knowledge Gaps

2.1 Tree Mortality under Climate Change

Forests cover approximately 31% of the global land surface and form a central component of the terrestrial biosphere (FAO, 2020). They underpin ecosystem structure, provide habitat for a large share of global biodiversity, and play a key role in climate regulation (IPBES et al., 2019; Intergovernmental Panel on Climate Change, 2021). Changes in tree survival therefore represent a fundamental indicator of ecosystem response to ongoing climate change (Hartmann et al., 2022).

Multiple lines of evidence from long-term forest inventories, ecological monitoring, and synthesis studies indicate that tree mortality rates have increased across many forested regions over recent decades (Trumbore et al., 2015; Hartmann et al., 2022). Assessments around the globe document drought-and heat-related tree mortality events on all forested continents since the late twentieth century, highlighting the widespread nature of climate-related mortality (Hammond et al., 2022; Network et al., 2025). These observations are consistent with rising air temperatures, increasing atmospheric evaporative demand, and changes in precipitation regimes associated with anthropogenic climate change (Intergovernmental Panel on Climate Change, 2021).

Tree mortality under climate change typically arises from interacting climatic stressors rather than isolated extremes. Prolonged drought, elevated temperatures, and increased vapour pressure deficit jointly impair physiological functioning and increase vulnerability to mortality (Hammond et al., 2022; Hartmann et al., 2022; Schuldt et al., 2020). The frequency and intensity of compound climate extremes have increased in many regions, contributing to mortality responses that exceed historical variability (Zscheischler et al., 2020; Weynants et al., 2024). However, the spatial extent, timing, and magnitude of climate-driven tree mortality remain heterogeneous across biomes and forest types, and are not yet consistently quantified at regional to global scales (Schiefer et al., 2024; Schwarz et al., 2025; Schuldt et al., 2020).

2.2 Consequences of Tree Mortality for Carbon, Energy, and Water Cycles

Tree mortality has direct and indirect consequences for the functioning of terrestrial ecosystems and their interactions with the climate system. The death of trees alters forest structure, reduces live biomass, and modifies surface properties that regulate exchanges of carbon, energy, and water between the land surface and the atmosphere (Trumbore et al., 2015; Hartmann et al., 2022).

Increased tree mortality can reduce carbon uptake by lowering photosynthetic capacity and, depending on decomposition rates and disturbance regimes, may lead to substantial carbon losses from biomass and soils (Trumbore et al., 2015; Weiskopf et al., 2024). Mortality-driven changes in canopy structure also influence surface albedo, roughness, and evapotranspiration, thereby affecting local and regional energy and water fluxes (Bonan, 2008; Anderegg et al., 2016). These effects can persist for years to decades following mortality events, particularly where regeneration is slow or incomplete.

At larger spatial scales, widespread tree mortality has the potential to alter regional carbon balances and hydrological regimes, with implications for climate feedbacks. However, the magnitude and persistence of these impacts depend strongly on disturbance intensity, forest type, climatic context, and post-disturbance recovery pathways (Bonan, 2008; Anderegg et al., 2016). Quantifying these consequences consistently across regions remains challenging, particularly where mortality is gradual or occurs in complex disturbance mosaics.

2.3 Role of Plant Functional Diversity in Tree Mortality Dynamics

The response of forests to climate-driven stress and mortality is mediated by biological characteristics of tree species and communities (Schuldt et al., 2020; Pickering et al., 2025). Plant functional traits related to water use, hydraulic safety, carbon allocation, and growth strategies influence both individual tree vulnerability and ecosystem-level responses to climatic extremes (Hartmann et al., 2022).

At the community scale, plant functional diversity has been hypothesised to buffer forests against climate stress by promoting complementary resource use, increasing resistance to disturbance, or enhancing recovery following mortality events (Mahecha et al., 2024; Isbell et al., 2015; Mori et al., 2013). Empirical evidence suggests that biodiversity loss can reduce ecosystem resilience and carbon storage, while diverse communities may show more stable functioning under environmental variability (Weiskopf et al., 2024). However, the strength and direction of biodiversity–mortality relationships vary across ecosystems and environmental gradients (Isbell et al., 2015; Pickering et al., 2025).

Despite growing interest in the role of functional diversity, most existing studies are limited to local or regional scales and rely on plot-based observations (Isbell et al., 2015; Mori et al., 2013; Sakschewski et al., 2016). As a result, it remains unclear how functional diversity modulates tree mortality risk under climate change at broader spatial scales, or how trait-mediated responses interact with climatic drivers and site conditions in different biomes.

2.4 Key Knowledge Gaps and Scientific Challenges

Despite substantial progress in understanding climate-related tree mortality, several key knowledge gaps continue to limit the ability to analyse its drivers and consequences at regional to global scales. First, spatially explicit and temporally resolved datasets that consistently capture tree mortality across biomes are still lacking (Network et al., 2025). Many existing Earth observation products focus on abrupt canopy loss or deforestation and are not designed to detect gradual dieback or climate-induced mortality processes (Schiefer et al., 2023; Cheng et al., 2024). In parallel, globally consistent information on plant functional diversity remains incomplete, limiting the joint analysis of mortality dynamics and biodiversity patterns across forest types and environmental gradients (Pereira et al., 2013; IPBES et al., 2019; Carmona et al., 2021).

Second, the absence of robust global forest mortality datasets constrains the quantification of tree mortality rates and associated biomass losses. While tree death represents a major transition of carbon from living biomass to dead organic matter pools , the spatial and temporal variability of mortality-related biomass loss is still poorly characterised at large scales (Trumbore et al., 2015; Network et al., 2025). This limits the ability to assess how climate-driven mortality contributes to changes in forest carbon stocks and potential carbon release pathways.

Third, robust attribution of observed tree mortality patterns remains challenging. Disentangling the relative roles of climate extremes, long-term climatic trends, plant functional diversity, and site conditions requires the integrated analysis of multiple data sources that are rarely combined in a consistent framework (Schiefer et al., 2024; Schwarz et al., 2025). While the Global Climate Observing System (GCOS) Essential Climate Variables and the Essential Biodiversity Variable (EBV) framework provide important foundations, they are seldom jointly exploited to assess how climatic stressors and ecological context interact to drive mortality (Pereira et al., 2013; IPBES et al., 2019; Bojinski et al., 2014).

Finally, the consequences of tree mortality for ecosystem functioning remain insufficiently quantified at regional to global scales. Mortality-induced changes in forest structure influence exchanges of carbon, water, and energy between ecosystems and the atmosphere, yet the links between observed mortality dynamics and ecosystem fluxes are still poorly understood (Trumbore et al., 2015; Anderegg et al., 2016). Addressing these interconnected challenges requires integrated, observation-based approaches that enable consistent monitoring, attribution, and impact assessment of tree mortality under ongoing climate change. Together, these gaps define the core scientific questions addressed by FORTRACK and motivate the science and methodological requirements outlined in this document.

3 Scientific Objectives and Conceptual Framework

Primary Scientific Questions and Specific Scientific Objectives

FORTRACK is guided by a set of interrelated scientific questions that address key gaps in the observation and analysis of climate-driven tree mortality and its ecological consequences at regional to global scales. The **primary scientific questions** are:

- How can tree mortality rates be quantified consistently across regions, forest types, and environmental gradients using spatially explicit Earth observation data?
- How do observed patterns of tree mortality translate into biomass loss and changes in forest carbon stocks at regional to global scales?

- To what extent can tree mortality be attributed to climate extremes, long-term climatic trends, plant functional diversity, and site conditions?
- How does tree mortality influence ecosystem fluxes of carbon, water, and energy, and how do these impacts vary across ecosystems?

These questions reflect the need for integrated, observation-based approaches that enable consistent monitoring, attribution, and impact assessment of tree mortality under ongoing climate change.

To address the primary scientific questions, FORTRACK pursues the following **specific scientific objectives**:

1. To exploit and integrate existing spatially explicit datasets to characterise tree mortality dynamics consistently across forested regions.
2. To quantify tree mortality rates and associated biomass losses, enabling assessment of impacts on forest carbon stocks.
3. To generate spatially explicit information on plant functional diversity and examine its relationship with observed tree mortality patterns.
4. To enable attribution of tree mortality dynamics to climatic drivers, plant functional diversity, and site conditions.
5. To assess the consequences of tree mortality for ecosystem fluxes of carbon, water, and energy across spatial scales.

These objectives define the scientific scope of FORTRACK and provide direct traceability to the science and methodological requirements specified in this document.

3.1 Conceptual Framework Linking Climate, Mortality, Biodiversity, and Ecosystem Function

FORTRACK adopts a conceptual framework in which tree mortality represents a central observable outcome of climate–ecosystem interactions. Climatic conditions and extremes, including drought, heat, and elevated atmospheric water demand, exert direct physiological stress on trees and strongly influence mortality patterns across spatial and temporal scales (Schiefer et al., 2024; Schuldt et al., 2020). These climatic influences are mediated by site conditions and ecosystem properties, resulting in heterogeneous mortality responses across forest types and environmental gradients.

In addition to direct climatic stress, biotic agents such as pests and pathogens represent important drivers of tree mortality in many forest systems. However, excess mortality associated with pests and diseases often coincides with periods of climatic extremes, as drought and heat stress reduce tree resistance and resilience to biotic attacks (Hartmann et al., 2022; Schwarz et al., 2025). Climate-induced weakening of host trees can therefore amplify the impacts of pests and pathogens, leading to large-scale mortality events that emerge from interacting climatic and biotic pressures rather than from single causal factors.

In this framework, tree mortality is understood in an observational sense and encompasses multiple manifestations. Standing deadwood provides a direct indicator of tree death and delayed mortality processes, while forest cover loss captures mortality associated with abrupt disturbance, management interventions such as sanitation logging, or rapid post-mortality canopy removal. Together, these complementary observations are required to characterise mortality dynamics comprehensively across regions. The use of both indicators, standing deadwood and forest cover loss, acknowledges that climate-related tree mortality may manifest either gradually or abruptly, depending on ecological and socio-environmental context.

Tree mortality alters forest structure and composition, with implications for ecosystem properties related to biomass, carbon storage, and exchanges of carbon, water, and energy between the land surface and the atmosphere. The magnitude and spatial distribution of these impacts depend on the extent, intensity, and form of mortality, as well as on ecosystem characteristics and post-mortality trajectories (Anderegg et al., 2016).

Plant functional diversity is treated as a key contextual property that may modulate both mortality patterns and ecosystem responses. Functional diversity is defined here as the diversity of plant trait expressions that characterise fitness, physiological functioning, and hydraulic strategies of plants. This includes both broadly integrative trait axes, such as those related to the leaf economics spectrum, as well as traits more specifically associated with water transport and drought sensitivity (Díaz et al., 2022; Bruelheide et al., 2018). Given that plant traits are often intercorrelated and coordinated, functional diversity is considered in a broad sense, encompassing not only aggregate diversity metrics but also the joint distribution and statistical moments of multiple traits at the community level.

Rather than resolving detailed physiological mechanisms, FORTRACK focuses on empirically characterising relationships between climate drivers, tree mortality observations, functional diversity patterns, and ecosystem indicators using spatially explicit data. This conceptual framework provides the basis for integrating climate variables, mortality information, biodiversity attributes, and ecosystem flux proxies within a coherent analytical perspective. It guides the formulation of scientific objectives and methodological requirements while remaining agnostic with respect to specific modelling or algorithmic implementations.

3.2 Relevance to IPBES, IPCC, and ESA EO Science Strategy

The scientific objectives of FORTRACK are aligned with priority research themes identified by the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES) and the *Intergovernmental Panel on Climate Change* (IPCC), particularly with respect to interactions between climate change, ecosystem integrity, biodiversity, and carbon cycling (IPBES et al., 2019; Intergovernmental Panel on Climate Change, 2021). By focusing on observation-based analyses of tree mortality and associated ecosystem responses, FORTRACK contributes to the scientific understanding required to support global and regional assessments of biodiversity–climate interactions.

The project is also aligned with ESA's Earth Observation Science Strategy, addressing the themes of ecosystem health and Earth system coupling through the integration of Essential Climate Variables, biodiversity-related information, and ecosystem indicators. By exploiting datasets developed within the ESA Climate Change Initiative alongside complementary Earth observation products, FORTRACK supports ESA's objective of advancing the scientific use of EO data to investigate interactions between climate and the biosphere, while remaining complementary to ongoing national and international research efforts.

FORTRACK is inherently cross-disciplinary, bridging expertise and data streams from the Earth observation, biodiversity, and climate research communities. The project integrates satellite observations from ESA missions, including the Copernicus Sentinel constellation, with derived Earth observation products such as Climate Change Initiative (CCI) Essential Climate Variables. These EO data are combined with biodiversity information from large-scale community and trait databases, including sPlot (Bruelheide et al., 2019), TRY (Kattge et al., 2020), and the Global Biodiversity Information Facility (GBIF), enabling spatially explicit analyses of plant functional diversity.

In addition, FORTRACK incorporates climate-related datasets that underpin contemporary climate research and assessment activities, including reanalysis products such as ERA5 produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), as well as climate indicators and concepts aligned with IPCC assessment frameworks (Intergovernmental Panel on Climate Change, 2021). By integrating these complementary data sources, FORTRACK bridges traditionally separate disciplines and enables analyses at the interface of climate dynamics, ecosystem change, and biodiversity patterns.

4 Scientific and Methodological Requirements

4.1 Requirements for Detection, Characterisation, and Benchmarking of Tree Mortality

The project shall support the detection and characterisation of tree mortality in a spatially explicit and temporally resolved manner across forested regions. This capability shall encompass different observable manifestations of tree mortality, including standing deadwood representing trees that are currently dead, as well as reductions in forest cover associated with trees that have died and have subsequently been removed through forest management practices, such as sanitation logging.

Earth observation–based forest disturbance products have advanced rapidly; however, most existing datasets are primarily designed to detect abrupt canopy loss associated with stand-replacing disturbances. As a result, they provide limited information on gradual mortality processes, do not reliably capture standing deadwood, and generally lack the ability to quantify fractional changes in forest condition, such as the proportion of standing deadwood or partial forest cover loss within a pixel. They are therefore poorly suited to detecting spatially scattered mortality patterns typical of climate-induced dieback. To date, the very recently released deadtrees.earth product represents a notable exception in that it provides high-spatial-resolution, spatially explicit information on both standing deadwood fraction and forest cover fraction, enabling the observation of gradual and spatially heterogeneous mortality patterns (Mosig et al., 2026). Preliminary studies indicate that deadtrees.earth is particularly well suited to detect climate- and extreme-induced tree mortality that does not manifest as immediate stand-replacing canopy loss and is therefore poorly captured by products optimised for abrupt forest cover change (Schiefer et al., 2023).

The deadtrees.earth dataset is derived using a supervised machine-learning approach that leverages a uniquely large archive of globally distributed drone imagery covering a wide range of forest types and biomass conditions (Mosig et al., 2026). High-resolution drone images, with spatial detail at the centimetre scale, enable robust pattern-recognition–based segmentation of forest cover and standing deadwood (Kattenborn et al., 2021; Schiefer et al., 2023; Möhring et al., 2025). These drone-based observations provide geospatially accurate and globally extensive reference data that are used to train satellite-based machine-learning models (Schiefer et al., 2023). Building on this training framework, deadtrees.earth exploits the full Sentinel-2 time series to map sub-pixel variability in forest cover and standing deadwood fractions on an annual basis 2017–present. Rather than relying on simple change detection, the approach applies machine-learning–based time-series analysis to resolve gradual and spatially scattered mortality processes and to quantify fractional changes in forest condition over time (Schiefer et al., 2023; Mosig et al., 2026).

However, the performance, limitations, and applicability of deadtrees.earth and other large-scale forest disturbance products must be evaluated systematically and comparatively. FORTRACK therefore requires benchmarking of candidate mortality and disturbance datasets against independent, spatially explicit reference information (see subsubsection 5.1.1 for considered disturbance products). Such benchmarking shall enable evaluation of detection performance across forest types, disturbance intensities, and mortality processes, including climate-related dieback, natural disturbances, and anthropogenic forest cover removal.

Robust benchmarking of tree mortality and forest disturbance products requires reference datasets with high spatial resolution and accurate geolocation, ideally based on airborne or very-high-resolution aerial imagery distributed across biomes. This requirement reflects known limitations of plot-based mortality observations, which are often spatially sparse, heterogeneous in design, and affected by geolocation uncertainties, constraining their suitability for large-scale benchmarking (Network et al., 2025). High-resolution aerial reference data are therefore essential to provide an objective basis for evaluating the detection performance of large-scale Earth observation–based disturbance products.

The benchmarking capability shall be supported by a methodological framework that enables fair and consistent comparison across products with differing spatial resolutions, temporal characteristics, and detection sensitivities. Benchmarking metrics shall be robust across a range of disturbance intensities and shall explicitly account for both omission (under-detection) and commission (over-detection) errors. The approach shall be scale-aware, acknowledging that different disturbance products are optimised for different spatial resolutions, minimum mapping units, and disturbance processes.

Within FORTRACK, high-resolution drone imagery from deadtrees.earth shall be used as a primary source of reference information for benchmarking (Mosig et al., 2026). Drone data enable precise identification of disturbed and undisturbed forest areas, accurate geolocation, and discrimination between major disturbance types (Kattenborn et al., 2019; Schiefer et al., 2023; Möhring et al., 2025). Benchmarking shall assess the performance of large-scale disturbance products across different disturbance intensities (e.g. fraction of affected area within a pixel) and across major disturbance categories, including (i) natural disturbances such as fires, landslides, flooding, and tsunamis; (ii) dieback associated with drought or pest outbreaks; and (iii) forest management activities, including sanitation logging, selective logging, and clearcuts. A detailed overview of disturbance types and reference data is provided in Table 1. All available large-scale forest disturbance and mortality products relevant to FORTRACK shall be included in the benchmarking exercise.

4.2 Requirements for Characterising Plant Functional Diversity

The project shall support the generation of spatially explicit, trait-based representations of plant functional diversity through the integration of ground-based biodiversity observations and Earth observation data (Lusk et al., 2025; Moreno-Martínez et al., 2018). This requirement explicitly acknowledges that currently available biodiversity observations are spatially sparse, heterogeneous in design, and unevenly distributed across regions and biomes. No single biodiversity data source provides sufficient spatial coverage or structural completeness to support robust, large-scale characterisation of plant functional diversity.

Previous research has demonstrated that expert-driven vegetation survey data, such as vegetation plots, provide among the most robust and ecologically meaningful representations of plant community composition and functional diversity (Bruelheide et al., 2018; Bruelheide et al., 2019). However, these datasets are inherently spatially sparse and geographically biased, limiting their direct applicability for spatially continuous analyses. In contrast, large-scale species occurrence datasets derived from multiple sources—including crowd-sourced observations and national or regional inventories—offer substantially greater spatial coverage and data volume, but are often opportunistic, uneven in sampling effort, and lack explicit community structure (Wolf et al., 2022; Schiller et al., 2021). Their large quantity and broad geographic extent nevertheless represent a critical advantage for reducing spatial data gaps (Wolf et al., 2022; Sharma et al., 2025).

The methodological framework within FORTRACK shall therefore support the combined use of complementary biodiversity data sources, linking community composition and species occurrence information with plant trait data to derive functional trait representations. Plant traits provide the functional link between biodiversity patterns and ecosystem processes, and all species occurrence and community datasets shall be linked to trait information to enable trait-based analyses.

The framework shall support representation of functional diversity beyond single summary metrics, enabling characterisation of trait distributions and variability within communities. This includes, but is not limited to, the derivation of statistical moments such as means, variances, and quantiles of trait distributions. Such representations are essential for analysing how functional diversity modulates tree mortality risk and ecosystem responses to climatic stress.

Earth observation data shall be used to support spatial extrapolation of trait-based information, enabling the generation of spatially continuous functional diversity products at resolutions suitable for integration with tree mortality and environmental driver datasets (Lusk et al., 2025). This integration enables representation of community-level functional diversity rather than relying solely on canopy-level signals detectable by remote sensing, which primarily reflect upper-canopy properties (Lusk et al., 2025; Wolf et al., 2022; Dechant et al., 2024). The integration of multiple biodiversity data sources is therefore required to maximise spatial coverage while maintaining ecological relevance and minimising extrapolation uncertainty in regions with sparse observations (Sharma et al., 2025).

4.3 Requirements for Quantifying Impacts on Biomass, Biodiversity and Ecosystem Functioning

FORTRACK requires the capability to quantify the impacts of tree mortality on forest biomass, carbon stocks, and biodiversity in a spatially explicit and globally consistent manner. Such integration is essential to estimate the amount of biomass transitioning from living vegetation to dead organic matter pools, which may ultimately contribute to atmospheric carbon emissions through decomposition. In principle, estimating mortality-related biomass loss is conceptually straightforward: spatially explicit forest datasets on aboveground biomass (AGB) are already available at global scale (Santoro et al., 2021), and when combined with fractional tree mortality or disturbance products (subsection 4.1), they allow estimation of dead biomass associated with observed mortality (Equation 1).

$$AGB_{\text{loss}} = \left(\frac{fraction_{\text{deadwood}} + fraction_{\text{forest loss}}}{fraction_{\text{forest}}} \right) \cdot AGB \tag{1}$$

$$AGB_{\text{deadwood}} = \frac{fraction_{\text{deadwood}}}{fraction_{\text{forest}}} \cdot AGB \tag{2}$$

$$AGB_{\text{forest cover loss}} = \frac{fraction_{\text{forest loss}}}{fraction_{\text{forest}}} \cdot AGB \tag{3}$$

The project shall therefore support the integration of global biomass datasets, such as those provided by the ESA Climate Change Initiative (ESA CCI Biomass Santoro et al., 2021, see subsubsection 5.1.2 for details), with spatially explicit tree mortality information to estimate mortality-related biomass loss. This includes the ability to account for sub-pixel variability in mortality, recognising that climate-induced dieback and partial canopy mortality often affect only a fraction of a pixel. In this context, the deadtrees.earth dataset (subsection 4.1) represents a particularly promising source of mortality information, as it explicitly captures both forest cover loss and standing deadwood at high spatial resolution, thereby enabling mortality-related biomass changes to be quantified separately for trees that remain standing (Equation 2) and for trees that have been removed , e.g. through sanitation logging (Equation 3).

To ensure the accuracy of these calculations, achieving optimal temporal alignment between detected mortality events and biomass reference data is a key requirement. Because radar-based observing systems, such as the ESA CCI Biomass product, are primarily sensitive to live vegetation and largely insensitive to dead wood, utilizing AGB measurements recorded after a disturbance has occurred would lead to a systematic underestimation of the biomass affected (Santoro et al., 2021). To mitigate this risk, the methodology shall prioritize the use of pre-disturbance AGB estimates to calculate biomass loss relative to when the trees were still alive and their biomass was fully visible to the satellite sensors. Given that deadtrees.earth provides annual mortality information from 2017 to 2025 and CCI Biomass provides discrete epochs up to 2022, the project will experiment with temporal lags of 1–2 years preceding the detected year of loss to ensure the radar signal represents a fully 'live' forest state. This approach is supported by the assumption that AGB remains relatively stable in undisturbed sites within these short windows, ensuring a robust baseline for quantifying the carbon impact of mortality pulses.

However, the project also requires explicit treatment of uncertainty associated with these estimates. In particular, observational limitations can lead to systematic biases in mortality detection and biomass attribution, given that EO-based disturbance products are limitted by occlusion: Dead trees may be obscured by surviving vegetation, while living trees may occur beneath standing deadwood (Schiefer et al., 2023; Mosig et al., 2026)). These effects are expected to vary with forest structure, biomass density, and mortality intensity. Direct observations suitable for assessing these variations and their impact on the uncertainty of estiamted mortality-related biomass loss at large scales remain sparse and heterogeneous (Network et al., 2025). To address these challenges, the project requires the use of forest growth modelling approaches as an independent means to characterise potential biases and uncertainty in mortality-related biomass estimates. Such models shall be capable of representing forest stands across a range of forest types and climatic conditions, including tree-level biomass, crown dimensions, and vertical structure. This enables assessment of how crown overlap, occlusion, and stand structure influence the relationship between observed mortality signals and actual biomass loss.

The outputs of these modelling approaches shall support two complementary objectives: first, to evaluate the robustness and potential biases of simple biomass–mortality integration approaches (Equation 1) under varying forest structural conditions; and second, to inform the development of uncertainty characterisation frameworks that relate uncertainty in biomass loss estimates to observable predictors such as forest biomass, mortality fraction, and forest cover.

In addition to biomass and carbon impacts, FORTRACK requires the capability to assess biodiversity impacts associated with tree mortality. This includes the integration of globally consistent functional diversity datasets (see subsection 4.2) with spatially explicit mortality information to identify diversity gradients, regions of elevated vulnerability, and potential hotspots where high mortality coincides with high functional diversity. Such analyses are essential to link observed mortality dynamics to biodiversity patterns and to assess the ecological consequences of climate-induced tree mortality at large scales.

Beyond impacts on biomass and biodiversity, FORTRACK requires the capability to assess the consequences of tree mortality for ecosystem functioning, particularly with respect to exchanges of carbon, water, and energy between forests and the atmosphere. This includes the use of ecosystem-scale flux observations to evaluate how mortality events affect gross primary productivity, net ecosystem exchange, evapotranspiration, and derived ecosystem functional properties. The methodological framework shall support the linkage of spatially explicit tree mortality information with site-level flux measurements to enable before–after comparisons of ecosystem functioning at affected sites, while accounting for background climate variability. The required data is described in subsubsection 5.1.5.

4.4 Requirements for Attribution of Tree Mortality Drivers

FORTRACK requires the capability to attribute observed tree mortality patterns to climatic drivers, ecosystem properties, and site conditions in a spatially explicit and locally resolved manner. Empirical attribution shall be performed at the level of individual pixels, enabling assessment of how driver importance varies across space, forest types, and environmental gradients. For this, local attribution methods will be used to derive variable importance maps from supervised models. For this, multiple local attribution techniques will be tested (Ribeiro et al., 2016; Sundararajan et al., 2017; Lundberg et al., 2017). The local attribution will be applied in a spatially and temporally consitent manner to derive attributions maps for different years.

The attribution framework shall support the joint analysis of tree mortality information with predictor datasets that differ in spatial resolution, temporal sampling, and data structure, including the dynamic integration of high-resolution mortality products with coarser-resolution climate reanalysis and Earth observation–derived environmental variables. The approach shall therefore accommodate flexible spatial and temporal aggregation, alignment, and scaling, ensuring consistent attribution analyses across datasets with differing resolutions. Given the global extent of the analyses, the high spatial resolution of mortality products, and the high temporal resolution of environmental data, attribution methods must be scalable and capable of efficiently handling very large, heterogeneous datasets. FORTRACK therefore requires analytical approaches that support efficient data loading, batching, parallel processing, and model training, enabling global-scale attribution analyses without prohibitive computational constraints.

A further key requirement is that attribution results are interpretable and scientifically transparent. Model performance and robustness shall be evaluated prior to interpretation to ensure that attribution results are based on reliable representations of observed mortality patterns (Schiefer et al., 2024; Sweet et al., 2023). The selection and implementation of specific modelling, interpretability, and computational tools are addressed in subsequent project tasks and guided by the requirements defined here.

5 Observational Data Requirements, Characteristics, and Candidate Sources

5.1 Overview of Dataset and Data Integration Requirements

The data to be integrated in FORTRACK span a wide range of spatial and temporal resolutions, data volumes, and formats, and must support joint analysis across disciplines. Data integration therefore represents a core scientific requirement.

5.1.1 Tree Mortality and Forest Disturbance Data

FORTRACK requires spatially explicit datasets that capture tree mortality and forest disturbance dynamics across forested regions in a temporally consistent and globally scalable manner. A key requirement is the ability to represent sub-pixel variability in forest condition, enabling quantification of partial canopy mortality and heterogeneous disturbance patterns within individual pixels. As outlined in subsection 4.1, FORTRACK prioritises the deadtrees.earth dataset as the primary candidate mortality product because it jointly provides spatially explicit fractions of standing deadwood and forest cover at high spatial resolution.

For integration within FORTRACK, tree mortality and disturbance datasets must be available in analysis-ready geospatial formats, support spatial tiling and scalable access, and provide consistent temporal sampling suitable for multi-year analysis. Key data characteristics include spatial resolution, temporal coverage, update frequency, and global coverage.

In addition to deadtrees.earth, FORTRACK requires the inclusion of alternative large-scale forest disturbance and tree mortality products for comparative benchmarking. These include optical and radar-based datasets that primarily capture canopy disturbance or forest cover loss, such as Global Forest Change, radar-based disturbance alert systems, and regional disturbance atlases. These products differ substantially in detection sensitivity, temporal resolution, and disturbance definitions. Candidate products considered for benchmarking are summarised in Table 1.

Table 1: Candidate large-scale forest disturbance and tree mortality products considered for benchmarking against deadtrees.earth.

Dataset	**Author**	**Spatial resolution**	**Available time**	**Available Coverage**	**Selected layers**
Global Forest Change (GFC)	Hansen et al. (2013)	30 m	2000-2024	Global	Yearloss
Radar for Detecting Deforestation (RADD)	Reiche et al. (2021)	10 m	from 2020	South America, Central America, Africa, Southeast Asia and the Pacific.	Alert; Date
European Forest Disturbance Atlas (EFDA)	Viana-Soto et al. (2024)	30 m	1985-2023	Europe	Annual disturbances; Latest disturbance

Disturbance Alert (DIST-ALERT)	Pickens et al. (2025)	30 m	2023-present	Global	Vegetation disturbance status; vegetation disturbance date
Latin America Woody Vegetation Structure and Change (LAM WVSC)	Potapov et al. (2021)	30 m	2015-2024	Latin America	Annual Woody Vegetation Structure Change; Disturbance year
Tree Canopy Height Europe (TCH)	Turubanova et al. (2022)	30 m	2001-2021	Europe	Tree removal; Tree removal lastest
deadtrees.earth	Mosig et al. (2026) and Schiefer et al. (2023)	10 m	2017-present	Global (inference in progress)	Forest Cover; Deadwood

5.1.2 Biomass and Carbon Stock Data

Quantification of mortality-related biomass and carbon impacts requires spatially explicit estimates of forest biomass that are consistent across regions and compatible with tree mortality datasets. The project therefore requires global or near-global biomass datasets that provide above-ground biomass estimates at spatial resolutions suitable for integration with spatially explicit mortality products.

A key candidate dataset is the ESA Climate Change Initiative Above-Ground Biomass (CCI AGB) product, which provides harmonised, spatially explicit global estimates of forest above-ground biomass for a set of discrete reference years (Santoro et al., 2021). The CCI AGB dataset forms a central foundation for assessing forest carbon stocks within FORTRACK and for quantifying biomass losses associated with observed tree mortality.

As the CCI AGB product is currently available only for selected epochs rather than as a continuous annual time series, FORTRACK will match years of observed tree mortality and disturbance with the nearest available biomass reference year preceding the event. Consistent with the requirements in Section 4.3, this prioritization of pre-disturbance AGB estimates ensures the radar signal captures the forest while trees were still alive. The project will experiment with temporal lags of 1–2 years preceding detected loss to establish a robust baseline, relying on the assumption that biomass typically does not change abruptly in undisturbed sites within these short temporal windows.

In addition, FORTRACK will liaise with the ESA CCI Biomass project team to explore the availability of extended time series or updated biomass products that could further improve temporal alignment between biomass and mortality datasets. Moreover, FORTRACK may also consider more recent biomass estimates derived from the ESA *BIOMASS* mission (Quegan et al., 2019).

5.1.3 Plant Trait and Functional Diversity Data

FORTRACK requires plant trait and functional diversity data that represent community-level ecosystem properties and enable spatially explicit analyses at regional to global scales. This requires the integration of species occurrence data and community composition information with plant trait databases in order to derive trait-based representations of vegetation communities. Meeting this requirement necessitates the combined use of multiple heterogeneous biodiversity datasets that differ in sampling design, spatial coverage, temporal resolution, and data quality.

A primary source of species occurrence information is the Global Biodiversity Information Facility (Yesson et al., 2007), which hosts the largest global collection of biodiversity observations, including major citizen science initiatives such as iNaturalist (Sullivan et al., 2014) and Pl@ntNet (Joly et al., 2014). These datasets provide unparalleled spatial coverage and sampling density, which is essential for extrapolating biodiversity and trait information to unsampled regions. However, GBIF-based observations are largely opportunistic and do not directly represent community composition, requiring careful aggregation and filtering to support community-oriented analyses (Wolf et al., 2022; Schiller et al., 2021; Sierra et al., 2024b).

Expert-driven vegetation survey data from the sPlot database provide high-quality, standardised information on plant community composition and functional diversity (Bruelheide et al., 2018; Bruelheide et al., 2019). Although spatially sparse relative to GBIF, sPlot data represent an excellent and indispensable source for calibration and independent validation of global trait-based and functional diversity products (Wolf et al., 2022; Dechant et al., 2024; Sharma et al., 2025). Importantly, previous studies have demonstrated that the combination of expert survey data with large-scale, opportunistic species occurrence datasets substantially improves the accuracy, robustness, and spatial representativeness of global trait and functional diversity mapping (Wolf et al., 2022; Lusk et al., 2025; Dechant et al., 2024).

Trait information is a central requirement for FORTRACK. The project therefore requires access to comprehensive, global plant trait datasets, with primary emphasis on the TRY database, which represents the largest harmonised collection of plant trait measurements worldwide and comprises millions of individual trait records (Kattge et al., 2020). Despite its unprecedented scope, trait coverage within TRY remains uneven across traits, taxa, and regions, with particularly strong gaps for many hydraulic and physiological traits and for species-rich but data-poor regions (Kattge et al., 2020). Therefore, the project shall make use of gap-filled trait datasets, which combine empirical observations with trait–trait relationships and taxonomic information to generate more complete and internally consistent trait representations (Joswig et al., 2023; Knighton et al., 2024).

A key data requirement is the harmonisation and integration of species lists across GBIF, sPlot, and TRY. This includes standardisation of taxonomic nomenclature, resolution of synonyms, and alignment of species identities across datasets to enable consistent linkage between occurrence, community, and trait information. Aggregation strategies are required to derive community-level trait representations from opportunistic occurrence data, acknowledging that individual GBIF observations do not directly correspond to vegetation plots (Wolf et al., 2022; Lusk et al., 2025).

The integrated biodiversity and trait datasets shall be coupled with Earth observation data to support spatial extrapolation and to generate spatially consistent functional diversity products suitable for integration with tree mortality and environmental driver datasets (Lusk et al., 2025). Relevant Earth observation–based predictor variables may include surface reflectance products, vegetation optical depth (VOD), as well as soil and climate information derived from satellite observations and reanalysis data, as summarised in Table 2.

5.1.4 Climate and Environmental Driver Data

Attribution of tree mortality to climatic and environmental drivers requires spatially and temporally explicit climate data that are physically coherent, consistent across regions, and compatible with Earth observation–based mortality and biodiversity datasets (subsection 4.4). FORTRACK therefore relies on the combined use of climate reanalysis products and satellite-derived Essential Climate Variables (ECVs) to characterise thermal conditions, moisture availability, atmospheric water demand, and climate extremes relevant to tree stress and mortality. These datasets shall be harmonised in space and time to capture both short-term extreme events and longer-term climatic trends, providing the foundation for robust, spatially explicit attribution analyses across forest types and climate regimes.

A central requirement is access to comprehensive climate reanalysis products that provide internally consistent, multi-decadal time series of key meteorological variables. In particular, FORTRACK requires the use of ERA5 and ERA5-Land reanalysis products produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). ERA5 provides global atmospheric and land-surface variables at a spatial resolution of approximately 25 km, while ERA5-Land offers enhanced representation of land-surface processes at higher spatial resolution (approximately 9 km). Together, these products provide temporally continuous information on near-surface air temperature, precipitation, soil moisture, radiation, wind, and atmospheric water demand, and enable the derivation of climate stress indicators such as drought intensity, vapour pressure deficit, and compound heat–drought extremes.

In addition to reanalysis data, FORTRACK requires climate-related Essential Climate Variables (ECVs) derived from Earth observation within the ESA Climate Change Initiative. Key CCI datasets relevant to the project include CCI Soil Moisture and CCI Land Surface Temperature, which provide observation-based constraints on environmental conditions (Dorigo et al., 2017; Dorigo et al., 2021; Merchant et al., 2019). These EO-derived datasets complement reanalysis products by offering independent, satellite-based information on surface moisture and energy states that are directly relevant to tree physiological stress.

5.1.5 Flux and Ecosystem Function Data

Assessing the impacts of tree mortality on ecosystem functioning requires long-term, high-quality observations of ecosystem–atmosphere exchanges and derived functional characteristics. FORTRACK therefore requires flux and ecosystem function data that enable analysis of both ecosystem carbon and water fluxes and emergent ecosystem functional properties, with sufficient temporal coverage to assess changes associated with tree mortality events.

The project requires measurements such as of gross primary productivity (GPP), net ecosystem exchange (NEE), and evapotranspiration to quantify how tree mortality alters ecosystem–atmosphere exchanges and carbon and water cycling. In addition, FORTRACK requires the derivation of ecosystem functional properties from flux time series. Following recent advances, such properties are defined as emergent system-level attributes that describe how ecosystems process energy, carbon, and water over time, rather than momentary flux magnitudes (Migliavacca et al., 2021; Musavi et al., 2017). Examples include light-use efficiency, intrinsic water-use efficiency, and characteristic response parameters of ecosystem carbon uptake to radiation or atmospheric demand.

A key requirement is the availability of temporally continuous, multi-year flux time series that allow comparison of ecosystem functioning before and after mortality events at individual sites. Such time series are essential to disentangle mortality-related effects from interannual climate variability and to assess potential recovery trajectories or persistent functional shifts following tree mortality.

Primary candidate data sources are eddy-covariance flux tower networks, in particular the Integrated Carbon Observation System (ICOS) (Heiskanen et al., 2022) and the FLUXNET global network (Pastorello et al., 2020). These networks provide high-frequency, ecosystem-scale measurements of carbon, water, and energy fluxes with established quality control and metadata standards. FORTRACK requires access to flux tower data from forest-dominated sites, with site selection informed by spatially explicit forest cover information. Tree cover fractions derived from deadtrees.earth shall be used to filter and stratify flux tower sites according to forest cover and exposure to tree mortality, enabling consistent linkage between flux observations and spatially explicit mortality data.

Gridded flux products such as FLUXCOM represent a potential complementary data source for broader-scale context and exploratory analyses (Jung et al., 2020; Mahecha et al., 2020; Montero et al., 2024). However, because these products are based on machine-learning upscaling of flux tower observations and have known limitations in representing ecosystem responses to extreme events and abrupt structural change, FORTRACK requires that analyses prioritise direct flux tower observations. The use of gridded flux products shall be considered only after successful implementation and evaluation of tower-based analyses.

Table 2 summarises candidate datasets and geospatial products that address the observational data requirements of FORTRACK across Earth observation, biodiversity, and climate domains.

Table 2: Candidate datasets and geospatial products addressing the observational data requirements of FORTRACK across biodiversity, Earth observation, and climate domains.

Variable / Data Type	**Source**	**Description and Relevance**
Crowd-sourced plant species occurrences	GBIF (incl. iNaturalist, PlantNet)	Global compilation of opportunistic plant species occurrence data providing unparalleled spatial coverage. Used to support extrapolation of plant trait and functional diversity information to global scale when linked with trait databases. Particularly valuable for capturing spatial gradients of diversity (Wolf et al., 2022; Lusk et al., 2025).
Expert-driven vegetation survey data	sPlot	Standardised vegetation plot database providing high-quality, community-level species composition data. Spatially sparse but essential for calibration and independent validation of trait- and diversity-based products derived from larger occurrence datasets (Wolf et al., 2022; Lusk et al., 2025; Dechant et al., 2024).
Plant trait observations	TRY	Largest global repository of plant functional trait measurements (Kattge et al., 2020). Provides trait information related to growth strategies, physiology, and hydraulic functioning. Central source for deriving community-level trait distributions when combined with GBIF and sPlot data.
Standing deadwood fraction and forest cover dynamics	deadtrees.earth	Spatially explicit global dataset providing fractions of standing deadwood and forest cover at high spatial resolution. Represents a key candidate for capturing gradual and climate-related tree mortality and sub-pixel mortality variability. Central dataset for mortality analysis, subject to systematic benchmarking against alternative products.
Above-ground biomass	ESA Climate Change Initiative (CCI) – Above-Ground Biomass	Global, harmonised estimates of forest above-ground biomass derived within the ESA CCI programme. Provides the basis for quantifying forest carbon stocks and estimating biomass losses associated with observed tree mortality.
Land surface temperature	ESA Climate Change Initiative (CCI) – Land Surface Temperature	Satellite-derived land surface temperature product providing observation-based information on surface thermal conditions. Relevant for analysing heat stress and temperature-related drivers of tree mortality and ecosystem responses.
Soil moisture	ESA Climate Change Initiative (CCI) – Soil Moisture	Global soil moisture dataset derived from multi-sensor satellite observations. Relevant for characterising drought conditions, soil water availability, and moisture-related drivers of tree mortality.
Burned area	ESA Fire Climate Change Initiative	Satellite-derived burned area product used to characterise fire disturbance as a potential driver or confounding factor in tree mortality analyses.

Variable / Data Type	**Source**	**Description and Relevance**
Land cover	ESA Climate Change Initiative (CCI) – Land Cover	Global land cover classification providing information on vegetation types and land-use context. Used to describe geographic patterns of forest cover and as a contextual variable in mortality analyses.
Plant functional type	ESA Climate Change Initiative (CCI) – Land Cover	Derived plant functional type information used to characterise broad vegetation strategies and as a co-variable in analyses of mortality and biomass patterns.
Topography	Copernicus DEM	Global digital elevation model providing elevation, slope, and terrain-related variables. Relevant for analysing site conditions influencing tree mortality patterns.
Meteorological and climate variables	ERA5 and ERA5-Land (ECMWF)	Global climate reanalysis products providing temporally continuous information on temperature, precipitation, radiation, wind, soil moisture, and atmospheric water demand. ERA5 (25 km) and ERA5-Land (9 km) enable analysis of both large-scale climate gradients and finer-scale land-surface processes relevant to tree mortality.
Long-term climate normals	WorldClim	Gridded global climate datasets providing long-term climatological summaries. Used to characterise background climate conditions and support extrapolation of functional diversity patterns to global scale.
Soil physical and chemical properties	SoilGrids	Global soil dataset providing spatially explicit information on soil texture, depth, and chemical properties. Relevant for characterising site conditions and supporting extrapolation of biodiversity and mortality patterns.
Climate forcing simulations	CMIP6 / ISIMIP3 (incl. hist-nat experiments)	Climate model simulations used to characterise anthropogenic versus natural climate forcing. Relevant for contextualising observed mortality patterns with respect to climate change attribution.
Fraction of absorbed photosynthetically active radiation (FAPAR)	JRC-TIP global products	Vegetation activity indicator derived from satellite observations. Relevant for analysing ecosystem functioning and potential impacts of tree mortality on energy and carbon fluxes.
Leaf area index (LAI)	Copernicus Global Land Service (CGLS)	Global LAI products providing information on canopy structure and vegetation density. Used to assess ecosystem responses and impacts of tree mortality on surface–atmosphere exchanges. (https://doi.org/10.24381/cds.7e59b01a)
Vegetation optical depth and related indices	VODCA database and related VOD datasets (e.g. Zotta et al., 2026)	Microwave-based vegetation indicators sensitive to vegetation water content and biomass. Relevant for supporting extrapolation of functional diversity and assessing vegetation stress patterns.
Terrestrial water storage	GRACE / GRACE-FO (ICGEM)	Satellite gravimetry-based estimates of terrestrial water storage. Relevant for analysing large-scale hydrological conditions and ecosystem water availability influencing tree mortality.

5.2 Overview of Data Needs, Integration Strategy, and Anticipated Limitations

FORTRACK requires the integration of heterogeneous datasets originating from Earth observation, biodiversity, climate reanalysis, and ecosystem flux measurements. These datasets differ substantially in spatial resolution, temporal sampling, data volume, uncertainty characterisation, and geographic representativeness. The overarching integration strategy therefore aims to minimise data manipulation wherever possible, in order to preserve information content and maintain analytical flexibility.

Integrating datasets with differing spatial and temporal resolutions introduces challenges related to scaling, harmonisation, and uncertainty. High-resolution tree mortality products must be combined with coarser climate reanalysis and Earth observation–derived environmental variables, requiring careful handling of spatial support, aggregation, and alignment. Given the large data volumes involved, the project prioritises dynamic data fusion within analysis pipelines rather than extensive pre-resampling of datasets. Where feasible, datasets will be rescaled, harmonised, and integrated on-the-fly within modelling and attribution workflows, for example through dynamic data loading during model training. This approach enables flexible experimentation with different spatial and temporal sampling strategies, model configurations, and parameter settings, while avoiding repeated generation of large intermediate data products.

Uncertainty information is heterogeneous across datasets and often incomplete or expressed using different metrics. Where uncertainty estimates are available, they will be harmonized and incorporated into modelling workflows (e.g. via weighting in ML model training). To specifically account for potential correlations between the sources of error across different datasets, we will implement multivariate weighting strategies. This approach will consider the error covariance structures between variables to ensure that observational uncertainties are appropriately propagated without overestimating or underestimating the combined error. These refined weights will be integrated into our xAI attribution framework to ensure that identified mortality drivers are robust even when predictor uncertainties are statistically linked.

FORTRACK will provide uncertainty information in two formats. Primary geospatial products for tree mortality and functional diversity will include continuous error metrics (Standard Deviation and Coefficient of Variation) to maintain full scientific precision and support high-resolution modeling. To facilitate the identification of significant mortality pulses (subsection 4.1), the project will also utilize confidence intervals derived from stochastic resampling and bootstrapping to quantify excess tree mortality rates. This dual approach follows recent guidance on uncertainty communication (e.g. Gruber et al., 2025), ensuring that technical data is provided for modelers while providing an interpretative framework for policy-relevant assessments.

Data gaps and biases further constrain integrative analyses. Biodiversity and trait datasets exhibit strong geographic variability in data density, with underrepresentation of many tropical regions despite high species diversity, as well as biases along accessibility gradients such as proximity to urban areas and research infrastructure (Sierra et al., 2024a). Trait databases are additionally biased towards certain taxonomic groups and traits (Kattge et al., 2020). These biases may imprint on functional diversity estimates and subsequent modelling results and will be explicitly considered during analysis and interpretation. The project shall also use concepts of coefficient of variation of ensenble estimations or the Area of Applicability (Meyer et al., 2021; Lusk et al., 2025).

5.3 Practical Constraints, Methodological Risks, and Mitigation Strategies

Tree mortality analyses within FORTRACK primarily rely on Sentinel-2–based products, in particular deadtrees.earth, due to their high spatial resolution and ability to resolve scattered mortality patterns commonly associated with climate extremes. As a consequence, most analyses are constrained to the period from approximately 2017 onward, when sufficient time series depth is available for robust forest cover and mortality mapping. Although Sentinel-2 was launched in 2015, reliable mortality detection requires multi-year observations (Schiefer et al., 2023).

Several ESA Climate Change Initiative datasets are available only for restricted time periods or at limited temporal resolution, including key products such as CCI Soil Moisture and CCI Land Surface Temperature (Dorigo et al., 2017; Dorigo et al., 2021; Merchant et al., 2019). Analyses will therefore be constrained to periods where tree mortality, climate, and environmental datasets overlap. Where critical temporal gaps are identified, FORTRACK will liaise with the corresponding ESA CCI product teams to explore the availability of extended time series, updated releases, or alternative product versions. Where extension is not feasible, analyses will proceed using the available data, and modelling will be restricted to periods of consistent overlap. For certain variables, such as above-ground biomass (Santoro et al., 2021), temporal variability is expected to be small relative to mortality-related changes, reducing sensitivity to limited temporal coverage.

For plant traits and functional diversity, the project will focus on temporally static trait representations rather than temporal changes, as current global biodiversity datasets (GBIF, TRY, sPlot) are too sparse and heterogeneous to support robust analysis of annual or interannual dynamics at global scale (Wolf et al., 2022; Lusk et al., 2025; Sharma et al., 2025).

Attribution analyses may be limited in regions where mortality products perform poorly or where environmental driver data are noisy or highly uncertain. In addition, some mortality drivers, such as pests and pathogens, are difficult to capture directly due to the lack of coherent global observations. As a mitigation strategy, information on past disturbance regimes may be used as proxies for biotic disturbance pressure where appropriate (Schwarz et al., 2025).

Differences in spatial representativeness and resolution pose challenges for linking fine-scale tree mortality patterns with environmental drivers and ecosystem response data. Flux tower observations represent local ecosystem conditions with temporally variable footprint areas (Migliavacca et al., 2021), whereas climate and environmental datasets used for attribution represent spatial averages over comparatively large extents (Schiefer et al., 2024). In addition, mortality products typically resolve patterns at spatial scales on the order of 10 m, while key environmental drivers such as ERA5 and ERA5-Land are available at coarser resolutions (approximately 25 km and 9 km, respectively). Climate extremes may further vary at finer spatial scales, particularly in topographically complex terrain where aspect, radiation exposure, and hydrological processes strongly modulate site conditions. To partially address these scale mismatches, high-resolution topographic data will be incorporated to better represent local environmental gradients.

Assessment of ecosystem impacts of tree mortality using flux data is additionally constrained by the availability and continuity of flux tower observations. Flux records may contain temporal gaps due to maintenance or instrumentation issues, and site availability varies across years and regions, limiting spatial coverage and temporal continuity of flux-based analyses. These limitations must be considered when interpreting observed changes in ecosystem carbon and water fluxes following mortality events. Analyses of ecosystem impacts will therefore focus on sites with sufficient data coverage and will explicitly account for background climatic variability when evaluating mortality-related flux responses.

6 Summary of expected Scientific Outputs, Impact, and Outlook

FORTRACK is expected to deliver a coherent set of scientific data products, analyses, and insights that advance the understanding of climate-related tree mortality and its consequences for ecosystems at regional to global scales. The anticipated outputs directly address the scientific objectives of the project and provide a foundation for integrated analyses of tree mortality, biodiversity, and ecosystem functioning.

Scientific Data Products: The project will produce spatially explicit scientific data products that integrate information on tree mortality, biomass, functional diversity, and climate drivers. Key expected outputs include a global benchmark of forest disturbance and tree mortality products using high-resolution aerial reference imagery, providing an objective assessment of product performance across disturbance types and intensities. FORTRACK will link global tree mortality time series based on deadtrees.earth with above-ground biomass information to derive spatio-temporal mortality-related biomass dynamics. These products will support the estimation of tree mortality rates and associated biomass losses at global scale, with aggregation at multiple spatial levels, including biomes and administrative units. In addition, the project will produce spatially explicit functional diversity layers at global scale, representing statistical moments of trait distributions for a broad spectrum of plant traits.

Scientific Analyses and Insights: Building on these data products, FORTRACK will deliver scientific analyses that characterise global patterns, gradients, and hotspots of tree mortality and associated biomass loss. Local attribution analyses will provide spatially explicit estimates of the relative importance of climatic extremes, functional diversity, environmental dynamics, and site conditions in shaping observed mortality patterns. The project will further assess the impacts of mortality pulses on ecosystem functioning by analysing changes in ecosystem-level fluxes and ecosystem functional properties before and after mortality events. These analyses will enable investigation of how functional diversity modulates ecosystem responses to climate-induced mortality and will provide evidence on potential biodiversity buffering effects at global scale.

Relevance to User Communities, Policy Processes, and ESA Activities: FORTRACK outputs are relevant to a broad range of user communities, including the Earth observation, climate, and biodiversity research communities. The results will contribute to the scientific evidence base underpinning global and regional assessments conducted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC), particularly with respect to climate–biodiversity interactions and ecosystem resilience. The project is designed to be complementary to ongoing ESA and international research activities and is embedded in multiple scientific collaborations with ESA Climate Change Initiative (CCI) teams. Through these collaborations, FORTRACK will both exploit existing CCI Essential Climate Variable products and provide structured feedback on their suitability, limitations, and potential improvement for analysing tree mortality, biomass dynamics, and ecosystem impacts. The scientific outputs and insights generated within FORTRACK will inform subsequent project tasks and support the continued development, integration, and exploitation of ESA Earth observation data within the wider international research landscape.

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