

FORTRACK

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

Report on the Establishment of Cloud In- frastructure and Workflows for Carbon Loss Estimates (Deliverable D2.2)

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CLIMATE-SPACE: BIODIVERSITY-CLIMATE STUDIES

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Contents

1	Introduction	2
1.1	Scientific Motivation and Knowledge Gaps	2
1.2	Integrated Infrastructure and Analytical Flexibility	2
1.3	Uncertainty Propagation and Validation	2
1.4	Iterative Delivery Roadmap	3
2	Methods and Implementation	3
2.1	Satellite products	3
2.1.1	deadtrees.earth tree cover change and mortality dataset	3
2.2	ESA Climate Change Initiative Biomass dataset	4
2.3	Calculation of biomass changes	4
2.4	Calculation of biomass changes	4
2.5	Validation and Uncertainty via FORMIND	5
2.5.1	FORMIND Forest Factory data	5
2.5.2	Validation using simulated forests	7
3	Results	8
4	Discussion and outlook	9
4.1	Critique of the Simulation Framework	9
4.2	Outlook and External Evaluation	9

1 Introduction

This report presents the first version (v1) of Deliverable D2.2, titled "Tailored datasets and/or tools published to an open-access repository on a cloud-based platform." As defined for the M6 milestone, this document serves to demonstrate that the FORTRACK project has successfully established the operational cloud environment and technical workflows required to generate high-resolution estimates of tree mortality-driven biomass and carbon loss.

1.1 Scientific Motivation and Knowledge Gaps

Forests represent one of the largest terrestrial carbon reservoirs, storing approximately 400–500 Pg C in aboveground biomass (Santoro et al., 2021). However, the stability of this sink is increasingly threatened by widespread forest disturbances and tree mortality events triggered by climate extremes, which mobilize substantial quantities of carbon—estimated at 5–15 Pg C annually (Hartmann et al., 2022; Network et al., 2025; Schiefer et al., 2024). Despite their importance, these transient carbon fluxes remain poorly constrained at global scales (Migliavacca et al., 2025). A major challenge in quantifying these pulses is that current global biomass datasets, such as the ESA CCI Biomass product, were not primarily designed to track annual disturbance-driven dynamics. Operating at spatial resolutions of 100 m, these products lack the sensitivity required to detect the subtle, scattered tree mortality characteristic of climate-induced stress (Schiefer et al., 2024; Cheng et al., 2024). Furthermore, radar-based biomass retrievals are predominantly sensitive to live vegetation and are largely insensitive to standing deadwood (Santoro et al., 2024). Utilizing biomass data alone after a mortality event would therefore lead to a systematic underestimation of the affected carbon, as the signal remains relatively stable despite the death of individual trees. To bridge this gap, FORTRACK integrates these biomass estimates with high-resolution (10 m) observations from the deadtrees.earth platform (Mosig et al., 2026b). Unlike conventional binary forest loss products, deadtrees.earth utilizes multi-temporal Sentinel-2 time series to produce annual maps that explicitly differentiate between tree cover loss and standing deadwood (Mosig et al., 2026a; Schiefer et al., 2023). Only by combining these fine-scaled disturbance and mortality tracks with wall-to-wall estimates of aboveground biomass can we accurately quantify the annual transition from living vegetation to dead organic matter.

1.2 Integrated Infrastructure and Analytical Flexibility

A central achievement of this project phase is the technical preparation of the compute and storage infrastructure at the University of Freiburg. This includes linking the cluster and HPC infrastructure of the Chair of Sensor-based Geoinformatics and the University of Freiburg respectively, with two critical data streams: the high-resolution mortality outputs of deadtrees.earth (Section 2.1.1) stored on the platforms storage as well as the global ESA CCI Biomass product (Section 2.2) stored on a network access storage at the University Freiburg's computing centre. This integrated environment was designed specifically to ensure analytical flexibility. By maintaining direct links between the processing cluster and these primary data repositories, the consortium enables flexible updating of its estimates as methodologies evolve or as updated products become available. For example, as the deadtrees.earth initiative produces new global-scale inferences from Sentinel-2 time series, these can be ingested directly into the FORTRACK pipeline to refine the resulting carbon loss maps. This ensures the project remains scalable and adaptable to the latest advancements in both mortality detection and biomass retrieval.

1.3 Uncertainty Propagation and Validation

The fusion of satellite products presents significant technical challenges, as both the mortality maps and the biomass datasets come with inherent measurement uncertainties (Mosig et al., 2026a; Santoro et al., 2024). To address this, the workflows documented here provide a robust method for uncertainty

propagation. Beyond simple measurement error, we integrate a framework to quantify uncertainty related to canopy occlusion, where surviving vegetation may obscure dead trees from the satellite's perspective (Schiefer et al., 2023). This framework leverages 700,000 simulated forest stands from the FORMIND process-based model to relate canopy-visible signals to true biomass dynamics (Henniger et al., 2023). These simulations provide the required "ground truth" to calibrate our uncertainty models for predicting the occlusion-related uncertainty, ensuring that the resulting estimates of carbon dynamics are accompanied by traceable and robust uncertainty metrics.

1.4 Iterative Delivery Roadmap

This v1 creation confirms that the technical foundation for global carbon loss estimation is complete. The tailored products will be iteratively refined in future releases: Version v2 (M9): Will deliver a dedicated uncertainty propagation and validation report. The global datasets will be uncertainty characterised and validated within this milestone. Uncertainty characterisation will account for (i) the measurement uncertainty of the ESA CCI Biomass product, (ii) the measurement uncertainty of the deadtrees.earth product, and (iii) uncertainty related to canopy occlusion, i.e., dead crowns occluded by living crowns and vice versa. Version v3 (M12): Will incorporate updated workflows and expand inference beyond the European baseline to global scale. Version v4 (M24): Will deliver the finalized global datasets and tools, supported by a comprehensive User Guide (D2.3).

2 Methods and Implementation

2.1 Satellite products

2.1.1 deadtrees.earth tree cover change and mortality dataset

The deadtrees.earth dataset provides global maps of forest mortality dynamics by estimating the fractional cover of standing deadwood and tree canopy cover at 10 m spatial resolution from Sentinel-2 time series (Mosig et al., 2026a). The product represents the proportion [%] of each pixel covered by (i) live tree crowns and (ii) standing deadwood. Changes in fractional tree cover enable capturing disturbance processes, such as harvest, windthrows or forest fires. Standing deadwood dynamics enable the identification of mortality events resulting from droughts, pests and pathogens. Moreover, the combination of fractional tree cover and standing deadwood enables to assess the relative mortality, that is how much of a given tree cover is dead. An interactive visualization of the product is available at <https://deadtrees.earth/deadtrees>.

The dataset is derived from a deep-learning framework trained with the largest globally distributed archive of drone imagery of forests, aggregated within the deadtrees.earth platform (Mosig et al., 2026b). These orthophotos typically have centimeter-scale spatial resolution (<10 cm) and were automatically processed using semantic segmentation models to identify tree crowns and standing deadwood (Möhring et al., 2025; Veitch-Michaelis et al., 2024). The resulting masks were aggregated to Sentinel-2 pixel scale to generate reference labels for model training (Mosig et al., 2026a). In total, the training dataset comprises more than 6 million labeled Sentinel-2 pixels derived from 2,600 orthophoto sites across all major forest biomes. In the recent months, thousands of additional orthophotos were made available, that will be used for retraining the models and generate improved tree cover and standing deadwood products.

Using the above-described drone-based labels, a deep learning model was trained to map Sentinel-2 reflectance time series to fractional tree cover and fractional standing deadwood cover (Mosig et al., 2026a). The model uses multi-year Sentinel-2 observations to capture seasonal and interannual spectral dynamics and produces annual maps from 2017 onwards at 10 m spatial resolution. The method leverages multi-temporal composites and transformer-based architectures to infer sub-pixel fractions of live and dead canopy. By explicitly distinguishing between standing deadwood and tree cover

loss, the dataset enables monitoring of mortality processes such as drought-induced dieback, insect outbreaks, or disturbance events that precede canopy removal.

The deadtrees.earth product (see availability under Section 4.2) is created as 30×30 km product in local UTM coordinates. For the present project, the individual UTM tiles are merged and resampled into a spatially coherent Cloud-optimized GeoTif in EPSG:4326.

2.2 ESA Climate Change Initiative Biomass dataset

The ESA Climate Change Initiative (CCI) Biomass dataset provides global estimates of above-ground biomass (AGB) density, expressed as oven-dry mass of woody vegetation (t/ha), which represents a key Essential Climate Variable for the global carbon cycle (Santoro et al., 2021). The product is generated using a retrieval algorithm that integrates multiple satellite observations sensitive to forest structure with ancillary ecological datasets and forest inventory statistics (Santoro et al., 2024).

The retrieval approach primarily relies on Synthetic Aperture Radar (SAR) observations from the ALOS-2 PALSAR-2 L-band mission and Sentinel-1 C-band mission, which provide sensitivity to vegetation structure and woody biomass through microwave backscatter. These observations are complemented by spaceborne LiDAR measurements from missions such as ICESat and ICESat-2, which provide structural metrics including canopy height and density that help constrain the relationship between radar backscatter and biomass (Santoro et al., 2024).

The algorithm combines these data streams within a parametric retrieval framework based on a water-cloud model, which relates radar backscatter to vegetation structure and biomass. LiDAR-derived structural relationships and subnational forest inventory statistics are used to parameterize the model globally. To reduce artefacts and temporal inconsistencies, annual biomass estimates are harmonized using a cost-function approach that minimizes spurious fluctuations arising from limited radar sensitivity to biomass variations.

Global biomass maps are produced at approximately 100 m spatial resolution, achieved through spatial aggregation of satellite observations and ancillary datasets to improve radiometric stability and reduce noise in the retrieval process. The resulting product provides spatially explicit estimates of AGB density for the year around 2020 and forms part of the ESA CCI long-term effort to generate consistent biomass time series for climate monitoring and carbon cycle research. The Biomass CCI annual AGB maps span the years 2007, 2010, and annually from 2015 to 2022. Complementing these, AGB change maps (expressed in Mg ha^{-1}) are available for consecutive year pairs (2016–2015, 2017–2016, 2018–2017, 2019–2018, 2020–2019, 2021–2020, and 2022–2021), for the decadal period 2020–2010, and for the earlier period 2010–2007.

The ESA CCI Biomass rasters is provided at $10^\circ \times 10^\circ$ tiles in EPSG:4326. For the time being, the carbon exchange product provided in FORTRACK is calculated on the basis of this raster configuration to avoid unnecessary data manipulation. Moreover, the tile structure facilitates parallel computing.

2.3 Calculation of biomass changes

2.4 Calculation of biomass changes

Aboveground biomass (AGB) dynamics are estimated by combining standing deadwood observations with tree-cover change (subsubsection 2.1.1) and spatial estimates from the ESA CCI Biomass data (subsection 2.2). The approach assumes that canopy fractions affected by tree mortality or tree-cover loss are proportional to the corresponding fraction of biomass affected within a pixel. The fraction of canopy area occupied by standing dead trees represents biomass that has transitioned to deadwood, whereas the fraction associated with tree-cover loss represents biomass removed from the canopy. To express biomass changes relative to the forested portion of each pixel, these fractions are normalized by the total tree-cover fraction. Under this formulation, total biomass loss (Equation 1) equals the sum

of biomass associated with standing deadwood (Equation 2) and biomass associated with tree-cover loss (Equation 3).

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

$$AGB_{\text{deadwood}} = \frac{fraction_{\text{deadwood}}}{fraction_{\text{forest}}} \cdot AGB \quad (2)$$

$$AGB_{\text{forest cover loss}} = \frac{fraction_{\text{forest loss}}}{fraction_{\text{forest}}} \cdot AGB \quad (3)$$

Small fluctuations in predicted canopy fractions can arise from classification noise, temporal inconsistencies between datasets, or residual model uncertainty. If directly propagated into biomass calculations, these minor variations could lead to inflated estimates of biomass change. To ensure conservative estimates and reduce the influence of such artefacts, threshold values are therefore applied to both forest-cover change and standing deadwood fractions before biomass changes are calculated. Specifically, only pixels with forest-cover change greater than 10% are considered to represent meaningful canopy loss, and only pixels with standing deadwood cover greater than 15% are considered to represent mortality-related biomass transitions. Values below these thresholds are set to zero prior to biomass calculations.

These thresholds were selected based on the validation error estimates of the respective deadtrees.earth model predictions (Mosig et al., 2026a). The deadtrees.earth error estimates were obtained through spatial block cross-validation to avoid overly optimistic accuracy estimates caused by spatial autocorrelation. The reference dataset was divided into 50 km spatial blocks in an equal-area projection, which were assigned to three outer folds. Model performance was evaluated on spatially independent test blocks, while validation blocks within each fold were used during hyperparameter tuning. Performance was assessed both as a regression task, using weighted Pearson’s correlation coefficient and weighted RMSE of fractional cover, and as a binary detection task, using precision and recall for distinguishing zero from non-zero cover values. We used the resulting RMSE values as guidance to define conservative thresholds of 10% for forest-cover change and 15% for standing deadwood cover, thereby retaining only canopy dynamics that exceeded the expected product-level prediction error. This thresholding reduces the propagation of model-induced fluctuations into biomass-change estimates and limits false-positive estimates of biomass loss and dead biomass.

Additionally, when the estimated deadwood fraction exceeds the tree-cover fraction within a pixel, the tree-cover fraction is set equal to the deadwood fraction to maintain physical consistency between canopy and deadwood estimates. This correction is only a temporary measure to address rare cases of inconsistent model predictions in the current product version, where the native constraint that tree cover must always be equal to or greater than deadwood cover was not fully enforced. Upcoming releases of the deadtrees.earth product are trained using an updated multi-task AI model that natively ensures consistent and physically plausible predictions of tree cover and standing deadwood cover, rendering this post-hoc correction unnecessary. After thresholding and consistency correction, the fractional layers are resampled to the raster configuration of the ESA CCI Biomass product (subsection 2.2) before calculating the biomass change components.

2.5 Validation and Uncertainty via FORMIND

2.5.1 FORMIND Forest Factory data

Validating satellite-based estimates of biomass dynamics that combine standing deadwood detection, tree cover change, and biomass products is challenging because no observational dataset provides consistent information on tree crown geometry, biomass, and spatial tree positions across large spatial

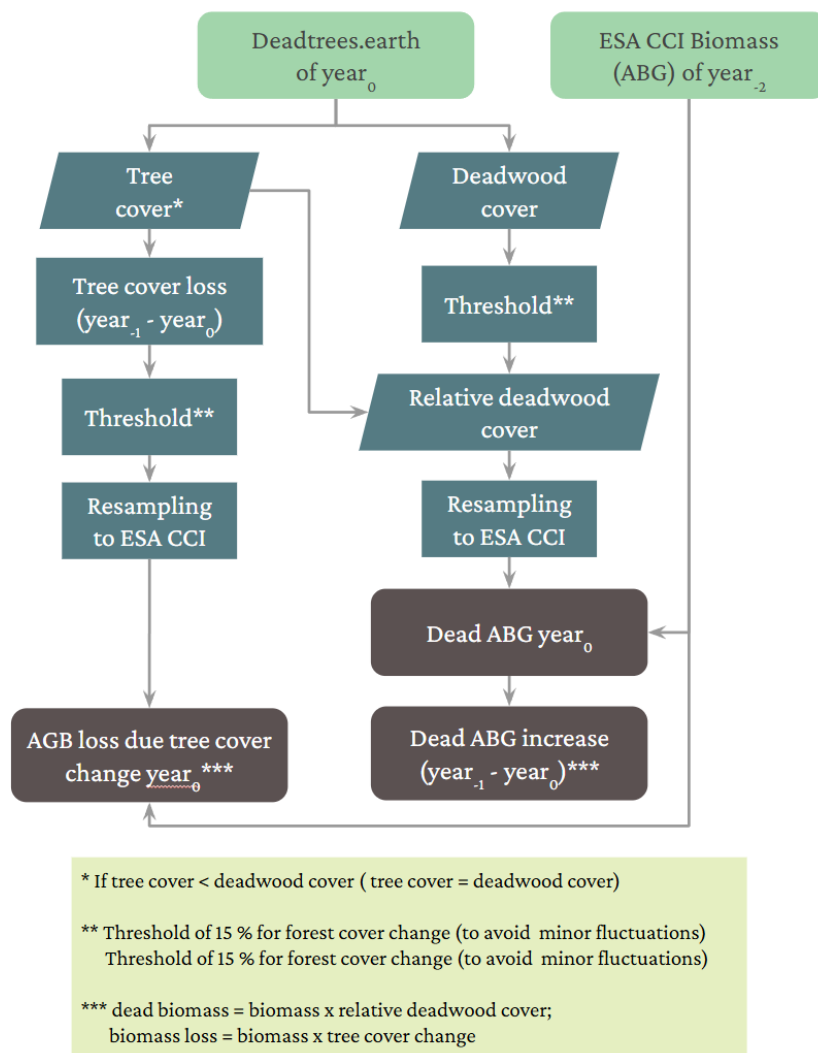


Figure 1: Workflow biomass change mapping using the deadtrees.earth and ESA CCI Biomass products.

scales and diverse forest types. Field inventories typically contain biomass measurements but lack spatially explicit crown geometry and vertical canopy structure, while remote sensing data capture canopy signals without direct information on the underlying tree-level biomass.

To address this limitation, we use simulated forest stands generated with the process-based forest model FORMIND (Köhler and Huth, 1998). FORMIND is an individual-based forest gap model that explicitly represents tree growth, recruitment, mortality, and competition. The model is calibrated and parameterized using empirical forest and tree-level data, including species- or plant-functional-type-specific allometric relationships, size distributions, growth rates, mortality rates, wood density, and crown-geometry parameters (Fischer et al., 2016). These empirical parameterizations allow FORMIND to simulate tree height, crown dimensions, biomass, and stand development in physical units. In the Forest Factory 2.0 framework, these calibrated FORMIND process representations and allometries are used to generate plausible forest stands across different ecoregions, while retaining explicit tree-level information on position, crown geometry, height, biomass, and mortality status.

The role of FORMIND in this study is specifically to quantify uncertainty related to canopy occlusion. Because both the true affected biomass and the canopy-visible projected crown fractions are known in the simulations, FORMIND allows us to evaluate how crown overlap and vertical forest structure influence the relationship between observable deadwood or canopy-loss signals and true biomass change. Thus, the traceability of the FORMIND-based component derives from the empirically calibrated process model, explicit tree-level simulation outputs, and unit-consistent aggregation to stand-level biomass values in t ha^{-1} .

The dataset consists of 700,000 simulated forest stands generated with the Forest Factory 2.0 framework using the individual-based forest model FORMIND (Henniger et al., 2023). The stands represent potential forest states across seven temperate and tropical ecoregions, including temperate forests in Central Europe (Germany) and the northeastern United States, as well as tropical forests in the Amazon basin, Panama, Ecuador, Malaysia, and Tanzania. Each stand covers an area of $20 \text{ m} \times 20 \text{ m}$ and together the dataset contains more than 11 million simulated trees with detailed structural and functional attributes.

Forest Factory generates forest stands by sequentially placing trees with species-specific allometries and height distributions while enforcing ecological constraints such as positive productivity, crown volume limits, and light competition between trees. These processes are derived from the individual-based forest model FORMIND, which simulates tree growth, mortality, recruitment, and competition to produce structurally realistic forest stands with plausible size distributions and canopy layering.

2.5.2 Validation using simulated forests

To evaluate the biomass-dynamics estimation framework under controlled conditions, we reproduced the same workflow that is applied to satellite data using simulated forest stands generated with FORMIND. The aim is to evaluate how well the combination of standing deadwood detection and tree cover change can recover actual biomass losses.

For each simulated stand, individual trees have known positions, crown sizes, tree height and biomass. To simulate mortality and disturbance events, we randomly sampled subsets of trees and assigned them as either standing dead trees or removed trees. Across simulations, we varied the proportion of affected trees between 0 and 100% of the stand. From these data we compute the projected crown cover of living trees, dead trees, and removed trees, explicitly accounting for crown overlap and occlusion (see Fig. 2 for an illustration). Based on these projections we derive two canopy metrics that mimic the satellite observations:

- Tree cover loss calculated from the projected area of removed tree crowns.
- Standing deadwood cover, derived from the projected crown area of dead trees. Standing deadwood cover is converted to relative deadwood cover by dividing dead crown cover by total tree cover, analogous to the deadtrees.earth product.

- Total stand biomass [t/ha], derived from the sum of all trees in a given area, effectively mimicking the ESA CCI Biomass product.

Using these metrics, we estimate biomass change in the same way as with satellite data, calculating biomass associated with standing deadwood (Equation 2), biomass associated with tree cover loss (Equation 3), and total biomass loss (Equation 1). These estimates are then compared with the true biomass values derived from the individual and randomly sampled dead or removed tree of the FORMIND stands, which provide the exact aboveground biomass change at the stand level. This comparison allows us to evaluate how accurately canopy-derived indicators recover true biomass dynamics across the ecoregions (subsubsection 2.5.1).

In addition, we compare the estimated biomass changes with the true FORMIND biomass under the assumption that biomass maps are perfectly accurate. This represents an idealized scenario equivalent to a world where satellite products such as deadtrees.earth and ESA CCI Biomass contain no measurement error.

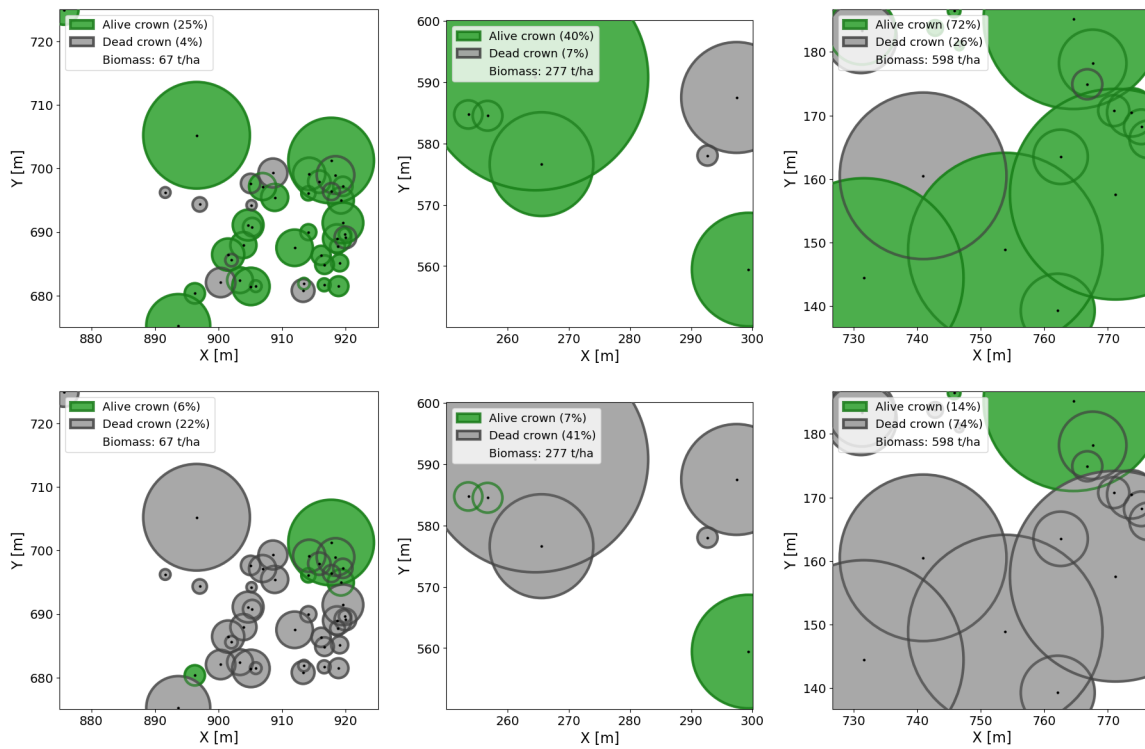


Figure 2: Simulated forest stands from the FORMIND Forest Factory (Henniger et al., 2023) with gradients of biomass and tree cover (left to right) and deadwood (top to bottom).

3 Results

Validation of the biomass change retrieval based on the FORMIND simulations shows very high agreement between estimated and true biomass losses, with an R^2 of 0.95 and an RMSE of 14.31 t/ha.

The qualitative evaluation across sites shows that the mapped biomass dynamics are spatially localized and occur over relatively small spatial extents (Figs. 4 and 5). This applies both to forest-cover loss, captured as biomass loss, and to tree-mortality dynamics, captured as dead biomass. The dead-biomass signal corresponds to mortality patterns visible within the forested landscape (Fig. 4), whereas biomass loss primarily reflects sanitation logging and clear-cuts that are apparent across the region (Fig. 5).

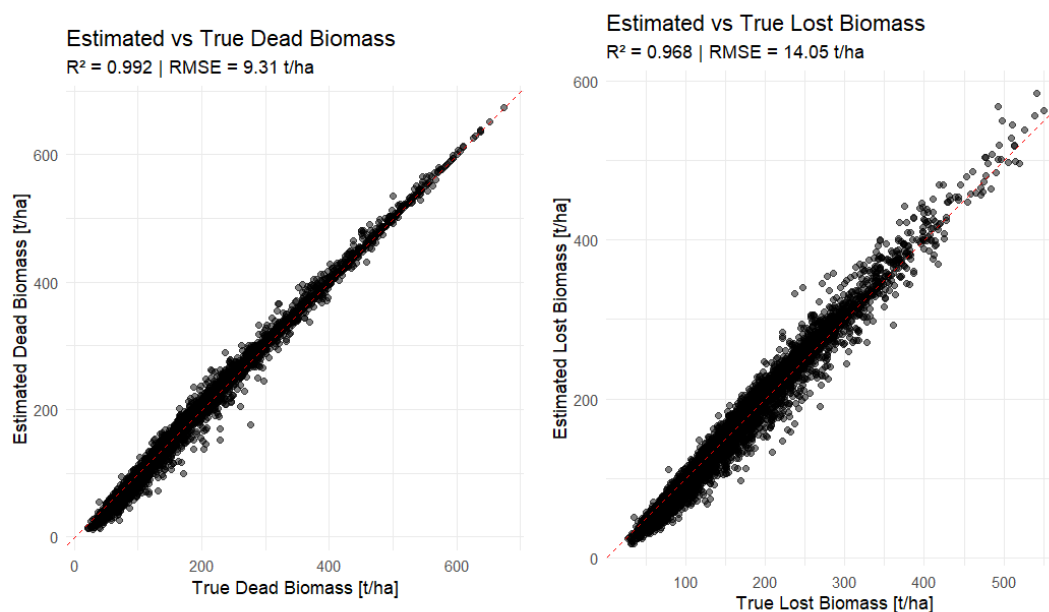


Figure 3: Validation of the biomass change retrieval.

4 Discussion and outlook

The integrated workflow presented in this report establishes a highly effective framework for quantifying high-resolution biomass dynamics. The controlled simulations using FORMIND revealed a strong capability to recover biomass losses with an R^2 of 0.95. Note that these preliminary estimates do not yet include the propagated product-level uncertainties of the deadtrees.earth and ESA CCI Biomass products.

4.1 Critique of the Simulation Framework

While the FORMIND Forest Factory provides a unique tree-level ground truth across diverse biomes, its reliance on random placement can create spatial clustering artifacts that may distort occlusion statistics compared to real-world forests. Furthermore, crown geometry simplifications (e.g., modeling crowns as hard-overlap circles) may misestimate actual canopy visibility and the complex spectral mixtures captured by satellites. Despite these limitations of the simulation framework, the approach remains the best available option for global validation given the lack of spatially explicit individual-tree inventories.

4.2 Outlook and External Evaluation

The project is now transitioning from infrastructure and implementation phase to broader scientific validation and global application:

Mortality Products: In mid-2026, the consortium will release the second version of the deadtrees.earth products. This updated version will be trained on an expanded dataset of more than 4,000

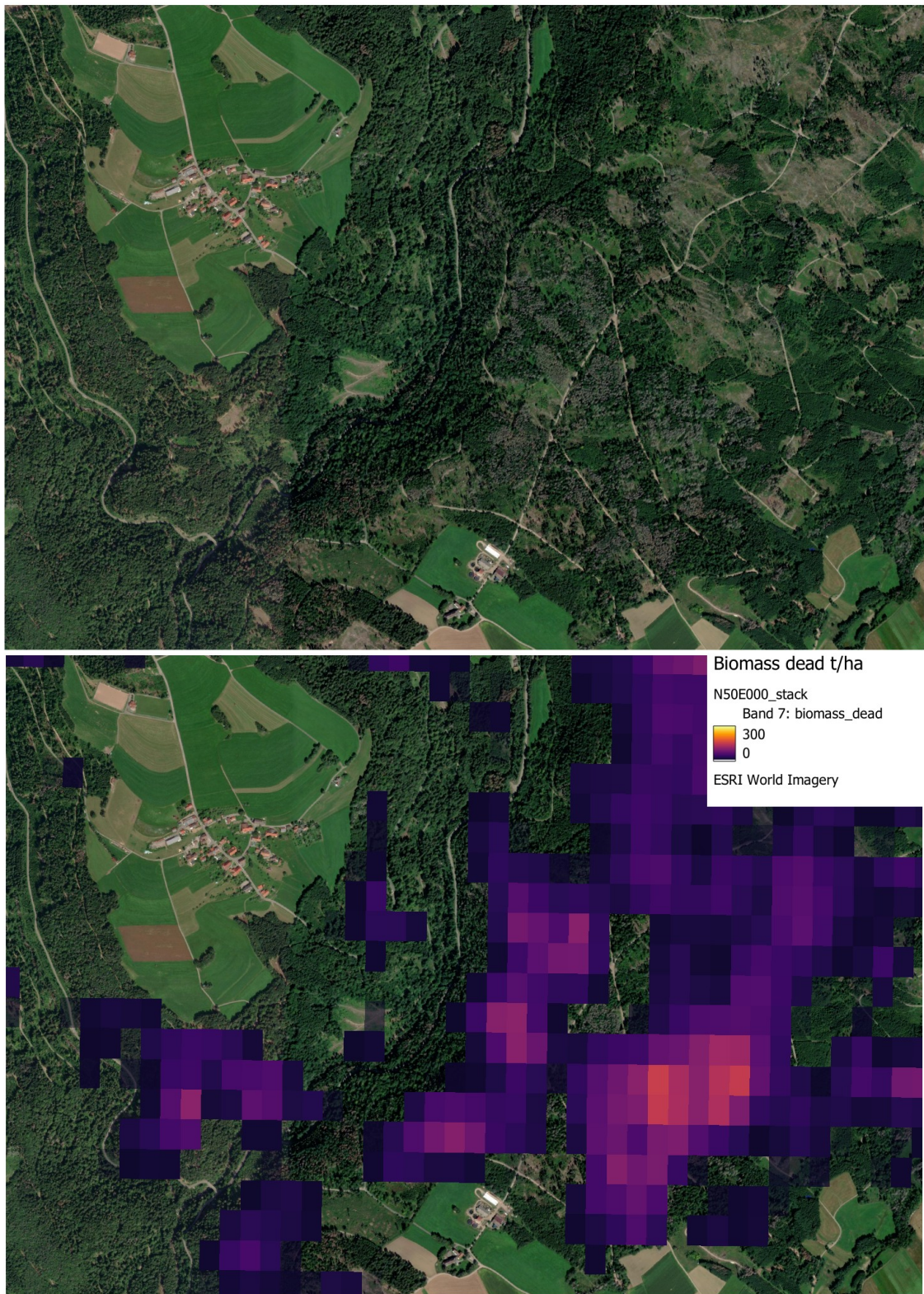


Figure 4: Example tile of the dead biomass (of standing deadwood) estimated from ESA CCI Biomass tile N50E000. The tile is available at <https://bwsyncandshare.kit.edu/s/rXR8eTLnCfitoP3>



Figure 5: Example tile of the lost biomass (related to tree cover change) estimated from ESA CCI Biomass tile *N50E000*. The tile is available at <https://bwsyncandshare.kit.edu/s/rXR8eTLnCfitoP3>

drone images. While the current product is already assumed to be highly accurate, this transition will provide even higher precision for detecting scattered mortality.

In-Depth Uncertainty Analysis

In the next project phase, we will further develop the uncertainty framework for the biomass-dynamics estimates. This will include the combined propagation of uncertainties from the underlying satellite products, namely the deadtrees.earth tree-cover and standing-deadwood estimates (Mosig et al., 2026a) and the ESA CCI Biomass product (Santoro et al., 2024). By integrating uncertainty information from both data sources, the resulting biomass-loss and dead-biomass estimates will be accompanied by traceable confidence metrics.

Beyond product-level uncertainties, we will also address structural uncertainties related to canopy occlusion. These arise because living and dead trees may partially or fully obscure each other in the canopy, so that the canopy-visible mortality signal does not always correspond directly to the true underlying biomass dynamics. To quantify this effect, we will explore the use of simulated forest stands from the FORMIND Forest Factory, which provide tree-level information on biomass, crown geometry, tree position, and mortality status. This will allow us to assess how forest structure and occlusion affect the relationship between visible deadwood or canopy loss and true biomass change.

Ground-Based Validation: To gain deeper insights into the accuracy of our satellite-derived maps, we are currently in contact with various research groups to incorporate ground-based forest loss estimates from inventories. This integration will provide a critical real-world benchmark to complement our simulated validation.

External Benchmarking: We are in active contact with the RECCAP-2 consortium to evaluate our methodology. This collaboration will allow for a comparative assessment of our biomass dynamics products against other independent global carbon cycle assessments.

European-Scale Implementation: The current processing pipeline has proven to be highly efficient, and we will soon apply the workflow to all ESA CCI Biomass tiles in Europe. In summary, this v1 baseline confirms that FORTRACK provides a robust and scalable technical foundation to bridge existing knowledge gaps in the global carbon cycle.

Code and Data availability

All implemented methods are available in the FORTRACK repository, including:

- **dead_biomass_estimation_v2.R:** The pipeline for combining the ESA CCI Biomass tiles with the deadtrees.earth forest cover and tree mortality layers. The output are tiles of biomass loss [t/ha], dead biomass [t/ha].
- **100_meter_Formind.R:** Workflow to compute crown projections based on the FORMIND forest factory data (Henniger et al., 2023).
- **deadwood_estimate_uncertainties.R:** Current workflow for the (theoretical) validation of dead biomass and related uncertainty estimation (preliminary) due to occlusion.
- **canopy_loss_estimate_uncertainties.R:** Current workflow for the (theoretical) validation of biomass loss and related uncertainty estimation (preliminary) due to occlusion.

A **sample tile** of the estimated carbon loss due to tree cover loss and tree mortality is provided at <https://bwsyncandshare.kit.edu/s/rXR8eTLnCfitoP3>.

All underlying data of the presented analysis are openly available:

- The *deadtrees.earth* dataset (Mosig et al., 2026a) is publicly available at https://data.rsc4earth.de/download/deadtrees.earth_maps/v1_europe_composite_epsg_3035/ and can be interactively explored at <https://deadtrees.earth/deadtrees>.
- The ESA CCI Biomass dataset (Santoro et al., 2024) is available through the ESA Climate Change Initiative data portal at <https://dx.doi.org/10.5285/95913ffb6467447ca72c4e9d8cf30501>.
- The FORMIND Forest Factory dataset (Henniger et al., 2023) is available on Zenodo under the title “Creating virtual forest around the globe and analysing their state space with the Forest Factory 2.0” at <https://zenodo.org/records/7920227>.

References

- Y. Cheng, S. Oehmcke, M. Brandt, L. Rosenthal, A. Das, A. Vrieling, et al. Scattered tree death contributes to substantial forest loss in California. *Nature Communications*, 15(1):641, 2024.
- Rico Fischer, Friedrich Bohn, Mateus Dantas De Paula, Claudia Dislich, Jürgen Groeneveld, Alvaro G Gutiérrez, Martin Kazmierczak, Nikolai Knapp, Sebastian Lehmann, Sebastian Paulick, et al. Lessons learned from applying a forest gap model to understand ecosystem and carbon dynamics of complex tropical forests. *Ecological Modelling*, 326:124–133, 2016.
- H. Hartmann, A. Bastos, A. J. Das, A. Esquivel-Muelbert, W. M. Hammond, J. Martínez-Vilalta, et al. Climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. *Annual Review of Plant Biology*, 73(1):673–702, 2022.
- Hans Henniger, Andreas Huth, Karin Frank, and Friedrich J. Bohn. Creating virtual forests around the globe and analysing their state space. *Ecological Modelling*, 483:110404, September 2023. ISSN 03043800. doi: 10.1016/j.ecolmodel.2023.110404. URL <https://linkinghub.elsevier.com/retrieve/pii/S0304380023001357>.
- Peter Köhler and Andreas Huth. The effects of tree species grouping in tropical rainforest modelling: simulations with the individual-based model FORMIND. *Ecological Modelling*, 109(3):301–321, 1998.
- Mirco Migliavacca, Giacomo Grassi, Ana Bastos, Guido Ceccherini, Philippe Ciais, Greet Janssens-Maenhout, Emanuele Lugato, Miguel D Mahecha, Kimberly A Novick, Josep Peñuelas, et al. Securing the forest carbon sink for the European Union’s climate ambition. *Nature*, 643(8074):1203–1213, 2025.
- Jakobus Möhring, Teja Kattenborn, Miguel D Mahecha, Yan Cheng, Mirela Beloiu Schwenke, Myriam Cloutier, Martin Denter, Julian Frey, Matthias Gassilloud, Anna Göritz, et al. Global, multi-scale standing deadwood segmentation in centimeter-scale aerial images. *ISPRS Open Journal of Photogrammetry and Remote Sensing*, page 100104, 2025.
- Clemens Mosig, Teja Kattenborn, David Montero Loaiza, Janusch Vanja-Jehle, John Brandt, Nathan Jacobs, Subash Khanal, Eric Xing, Martin Schwartz, Helene C Muller-Landau, et al. Sub-pixel mapping of disturbance and tree mortality dynamics from Sentinel-2 time series around the globe. *EarthArXiv*, 2026a.
- Clemens Mosig, Janusch Vajna-Jehle, Miguel D Mahecha, Yan Cheng, Henrik Hartmann, David Montero, Samuli Junntila, Stéphanie Horion, Mirela Beloiu Schwenke, Michael J Koontz, and Teja others, Kattenborn. *deadtrees.earth*—an open-access and interactive database for centimeter-scale aerial imagery to uncover global tree mortality dynamics. *Remote Sensing of Environment*, 332:115027, 2026b.
- International Tree Mortality Network, Cornelius Senf, Adriane Esquivel-Muelbert, Thomas AM Pugh, William RL Anderegg, Kristina J Anderson-Teixeira, Gabriel Arellano, Mirela Beloiu Schwenke, Barbara J Bentz, Hans Juergen Boehmer, et al. Towards a global understanding of tree mortality. *New Phytologist*, 245(6):2377–2392, 2025.

- M. Santoro, O. Cartus, N. Carvalhais, A. Araza, S. Willcock, et al. The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations. *Earth System Science Data*, 13(8):3927–3950, 2021.
- Maurizio Santoro, Oliver Cartus, Shaun Quegan, Heather Kay, Richard M Lucas, Arnan Araza, Martin Herold, Nicolas Labrière, Jérôme Chave, Åke Rosenqvist, et al. Design and performance of the climate change initiative biomass global retrieval algorithm. *Science of remote sensing*, 10:100169, 2024.
- F. Schiefer, S. Schmidlein, A. Frick, J. Frey, R. Klinke, K. Zielewska-Büttner, et al. Uav-based reference data for the prediction of fractional cover of standing deadwood from sentinel time series. *ISPRS Open Journal of Photogrammetry and Remote Sensing*, 8:100034, 2023.
- F. Schiefer, S. Schmidlein, H. Hartmann, F. Schnabel, and T. Kattenborn. Large-scale remote sensing reveals that tree mortality in germany appears to be greater than previously expected. *Forestry: An International Journal of Forest Research*, page cpae062, 2024.
- Josh Veitch-Michaelis, Andrew Cottam, Daniella Schweizer, Eben N Broadbent, David Dao, Ce Zhang, Angelica A Zambrano, and Simeon Max. Oam-tcd: A globally diverse dataset of high-resolution tree cover maps. *Advances in neural information processing systems*, 37:49749–49767, 2024.