Spacetwin: virtual forest for monitoring disturbances from space

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Forest disturbances, such as windthrow events, drought, pest outbreaks, and wildfires, are increasingly affecting forests globally. With climate change, these disturbances are projected to intensify in both frequency and severity, posing significant challenges for sustainable forest management (Seidl et al. 2017, McDowell et al. 2020).

Currently, we have access to a diverse set of freely available satellite datasets (i.e. passive optical, radar and LiDAR), which are a crucial tool for monitoring forest disturbances. Satellite remote sensing has two key advantages: the ability to monitor large areas and the possibility of near-real-time processing. Satellite observations are a proxy of the variables of interest, and field measurement are required for calibration and validation. However, satellites have limited spatial and temporal resolution and coverage makes it harder to integrate field observations. This is especially relevant for disturbances as they have an irregular spatiotemporal distribution. We are often limited in our understanding of the direct physical link between changes in forest and what can be observed from a satellite (Calders et al. 2025) which limits our ability to separate different effects, quantify uncertainties and identify which sensor, or combinations of sensors, is best suited for a specific use case.

The SPACETWIN project aims to address this challenge by using radiative transfer modeling (RTM) on high-fidelity virtual forests. In this context, RTM is the simulation of electromagnetic radiation interacting with the forests, thus predicting what a satellite would see above that specific forest. This provides a link between the forest structure and the satellite observations. The use of simulations allows us to control the conditions in the forest. For instance, if the goal is understanding how to monitor defoliation, one would run simulations with different amount of leaves. This enables us to understand how the satellite signal differs and what other parameters influence the observation (e.g. stem density). Moreover, RTM simulations can be done at different wavelengths, from optical to microwave, allowing to test different types of satellite sensors.

Following the forward modeling phase (i.e. predicting satellite observations from 3D forests), we employ emulation techniques to invert the RTM and train machine learning models to predict forest conditions from satellite observations. The strength of this approach is the ability to generate an extensive, high-quality dataset that enables developing robust detection algorithms and quantifying uncertainties.

The virtual forests are created by measuring the forest in detail using a terrestrial laser scanning (TLS). The SPACETWIN project has already acquired an extensive dataset across a wide range of forest types and disturbances. TLS collects a point cloud, from which each individual tree in the point cloud is segmented. Subsequently Quantitative Structural Models (QSM) are built. They represent the woody parts of the tree as a set of cylinders. In this way every single branch in the forest is explicitly measured and modelled. Leaves are added to the QSM to obtain the complete virtual forest, which is used as an input for the RTM model.

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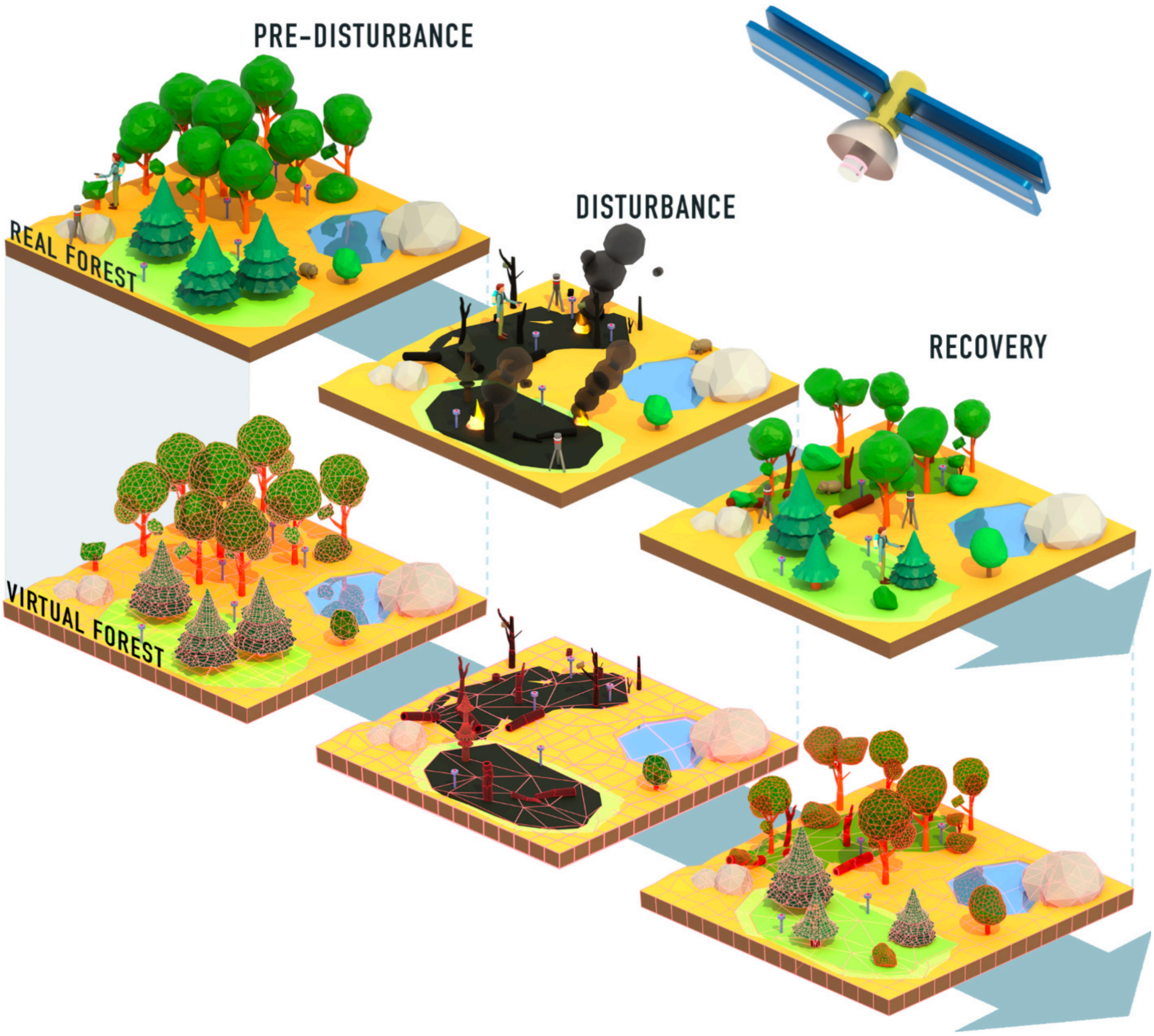

Figure 1. Conceptualisation of virtual forests across a disturbance and recovery gradient. Source: Calders et al. (2025)

The processing pipeline is semi-automated as there are steps such as segmentation and QSM quality control which currently require manual intervention. However, this is an active area of research with promising development. Overall our results show that the technology is mature and it would be possible to deploy it at scale.

For researchers, virtual forests provide unprecedented capability to understand the drivers behind forest disturbances and recovery processes, disentangling complex interactions between forest structure, disturbance type, and the satellite signal. For forest owners and managers, the results of the SPACETWIN project will result in monitoring systems that can better detect disturbances, attribute them more accurately, and support timely decision-making for salvage operations and risk management.

Looking forward, as TLS technology becomes more accessible and cost-effective, the framework can be expanded to build new virtual forests adapted to local conditions, enabling region-specific calibration of satellite monitoring systems. This scalability ensures that SPACETWIN's innovations can translate into operational tools for forest management across Europe.

Bibliography

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