Using dense optical time series for intra-annual forest disturbance detection in Germany

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Forest ecosystems in Central Europe have been increasingly affected by natural disturbances, such as storms, droughts and bark beetle outbreaks, requiring improved monitoring strategies. Effective detection of these disturbances remains a significant challenge, especially when considering long-term dynamics. Earth Observation (EO) has proven essential for monitoring and analysing disturbances at large scales. Most current approaches focus either on high temporal detail, using sensors like Sentinel-2, or on long-term change detection using the Landsat archive. Sentinel-2 allows for detailed intra-annual mapping, but its relatively short archive limits the assessment of long-term trends. While Landsat offers a multi-decadal record, it often lacks the temporal frequency to detect disturbance events within a year. Knowledge of disturbance timing is, however, crucial for understanding drivers and producing maps relevant for forest management and planning. This contribution addresses this gap by using dense time series from both Landsat and Sentinel-2 to improve the temporal accuracy of disturbance detection. To achieve this, we processed all Landsat and Sentinel-2 images available over Germany into a standardised data cube using the operational FORCE software framework. Following, we used harmonic models to identify observations that deviate from model predictions and thus might indicate a disturbance event. To set a stable reference period for fitting the harmonic models, we used existing annual disturbance maps to separate each pixel's time series into a stable pre-disturbance period and a disturbance period for which observations were checked against model predictions. We tested our approach in five regions with extensive storm-related damage: Lower Saxony and Saxony (Storm Friederike, 18 January 2018), Sauerland (Storm Kyrill, 19 January 2007), the Black Forest (Storm Lothar, 26 December 1999), and North Rhineland-Palatinate (Storm Vivian–Wiebke, 1 March 1990). For testing and validation, we manually labelled 200 reference pixels of confirmed storm events with exact disturbance dates. Based on this reference dataset, we evaluated how varying thresholds, vegetation indices, data densities, and disturbance characteristics influence detection performance. A particular emphasis was placed on assessing whether integrating Sentinel-2 improves intra-annual detection accuracy for Storm Friederike, which occurred after the launch of Sentinel-2, or whether Landsat data alone are suitable for intra-annual disturbance detection. For the storms observed only by Landsat, our method detected 50% of disturbances within 63 days and 95% within 98 days of occurrence. For Storm Friederike, the availability of observations from both sensors substantially improved performance, reducing the median detection lag to 31 days, with 95% of events detected within 68 days. Detection errors varied between storms, primarily due to differences in observation density. By enabling timely detection, our approach will advance existing annual disturbance products to include the

exact timing of disturbances, thereby improving the subsequent analysis of disturbance drivers (i.e., separating storm and bark beetle disturbances from regular harvests). This information is particularly important for understanding recent changes in natural disturbances across Europe and how management has responded, ultimately improving future management options.

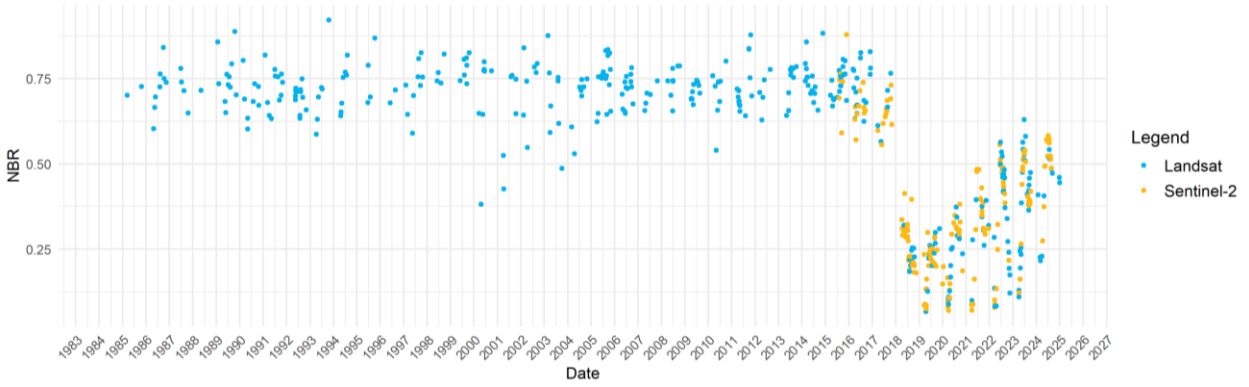

Figure 1. Time series of a pixel in the Harz Mountains, Germany, affected by storm Friederike on 18 January 2018

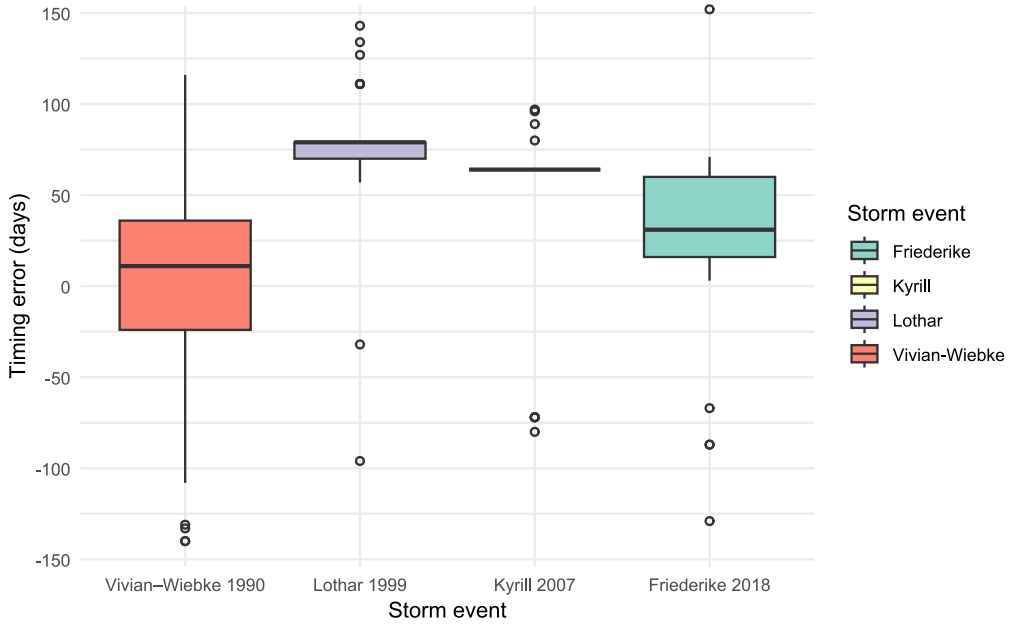

Figure 2. Distribution of detection timing errors (days) relative to reference storm dates for different storm years.