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RESEARCH ARTICLE

The Database of European Forest Insect and Disease Disturbances: DEFID2

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Abstract

Insect and disease outbreaks in forests are biotic disturbances that can profoundly alter ecosystem dynamics. In many parts of the world, these disturbance regimes are intensifying as the climate changes and shifts the distribution of species and biomes. As a result, key forest ecosystem services, such as carbon sequestration, regulation of water flows, wood production, protection of soils, and the conservation of biodiversity, could be increasingly compromised. Despite the relevance of these detrimental effects, there are currently no spatially detailed databases that record insect and disease disturbances on forests at the pan-European scale. Here, we present the new Database of European Forest Insect and Disease Disturbances (DEFID2). It comprises over 650,000 harmonized georeferenced records, mapped as polygons or points, of insects and disease disturbances that occurred between 1963 and 2021 in European forests. The records currently span eight different countries and were acquired through diverse methods (e.g., ground surveys, remote sensing techniques). The records in DEFID2 are described by a set of qualitative attributes, including severity and patterns of damage symptoms, agents, host tree species, climate-driven trigger factors, silvicultural practices, and eventual sanitary interventions. They are further complemented with a satellite-based quantitative characterization of the affected forest areas based on Landsat Normalized Burn Ratio time series, and damage metrics derived from them using the LandTrendr spectral–temporal segmentation algorithm (including onset, duration, magnitude, and rate of the disturbance), and possible interactions with windthrow and wildfire events. The DEFID2 database is a novel resource for many large-scale applications dealing with biotic disturbances. It offers a unique contribution to design networks of experiments, improve our understanding of ecological processes underlying biotic forest disturbances, monitor their dynamics, and enhance their representation in land-climate models. Further data sharing is encouraged to extend and improve the DEFID2 database continuously. The database is freely available at https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/FOREST/DISTURBANCES/DEFID2/.

KEYWORDS
bark beetle, biotic forest disturbances, climate change, defoliator, forest carbon cycle, forest resilience, pest monitoring, tree mortality

1 | INTRODUCTION

Insect and disease outbreaks are among the most impactful biotic forest disturbances as each year they affect forests across tens of millions of hectares globally, especially in temperate regions of the Northern Hemisphere (Kautz et al., 2017; van Lierop et al., 2015). According to national statistics in the database of forest disturbances of the Food and Agriculture Organization (FAO) of the United Nations, insects and diseases affected on average more than 1 million hectares annually in Europe over the period 2000–2017, accounting for more than 50% of the total naturally disturbed forest area (FAO, 2022). Warming-induced reductions in plant defense mechanisms appear to contribute to recent increases in forest vulnerability to insect disturbances (Forzieri et al., 2021) and are expected to be further compromised by climate change (Seidl et al., 2017). Forest cover losses from insect disturbances could lead to detrimental effects on the stability and sustainability of forest ecosystems (Richter et al., 2022; Trumbore et al., 2015). Specifically, key forest ecosystem services, such as carbon sequestration, the regulation of water flows, wood production, the protection of soils, and the conservation of biodiversity, could be jeopardized in the near future (Seidl et al., 2014, 2018).

Signs that this is happening are emerging. After decades in which global forests became a stronger carbon sink (Friedlingstein et al., 2019; Pan et al., 2011), the ability of European forests to provide such a sink appears to be saturating. This phenomenon has been associated with an increased frequency and duration of natural disturbances (Nabuurs et al., 2013). In Canada, insect disturbances driven by rapid climate change turned forests from carbon sinks into national carbon sources (Kurz et al., 2008). If climate change not only increases the duration and intensity of natural disturbances but also decreases the capacity of forests to recover from them, that is, lowers their resilience, then ecological regime shifts will become more likely (Forzieri et al., 2022; Patacca et al., 2023; Smith et al., 2022).

Recent studies indicate the extent of damage caused by natural disturbances in Europe, and the share of different agents in it; bark beetles caused 17% of the estimated 43.8 million m^3 of wood damaged annually by natural disturbances in Europe between 1950 and 2019 (storms accounted for 46% and fires for 24%; Patacca et al., 2023). However, bark beetle disturbance doubled its share of the total damage in the last 20 years. Despite the impact of biotic agents such as forest pests and diseases on ecosystem services, there are currently no spatially detailed databases that gather disturbances records caused by these agents in Europe with a harmonized protocol. Large-scale reference observations could help develop our understanding of the processes driving changes in disturbance regimes across wide environmental gradients and the quantification of their current and future impact on the biosphere.

Despite the lack of systematic collection of geospatial insect and disease disturbance records in European forests (Senf et al., 2017), many research-driven initiatives have mapped insect infestations and disease outbreaks over the last decades. These records are of great value to characterize and understand forest disturbances locally. However, using them at the European scale has thus far been extremely challenging; data collected through different, uncoordinated initiatives are not easily compiled, and are typically documented following diverse standards. The EU Forest Strategy for 2030 aims to improve this situation through collaboration on monitoring forest diseases and pests (European Commission, 2021).

Challenges in documenting biotic disturbance patterns in forests are not unique to Europe. A recent review highlighted the substantial lack of monitoring systems for biotic disturbances across the globe (Kautz et al., 2017). Notable examples of insect and disease disturbance mapping systems that do cover large geographical areas include the Insect & Disease Surveys (IDS) program of the United States Department of Agriculture (USDA; USDA Forest Service, 2022) and the National Forestry Database (NFD) of the Canadian Forest Service (CFS; Canadian Forest

Service, 2022). These mapping systems are based on annual aerial and ground surveys and have some variation in consistency and accuracy, as they involve distinct surveyors and methods. Nonetheless, these data collections have undoubtedly provided crucial insights into the key drivers of biotic disturbances in North America and their potential effects on carbon cycling and forest ecosystem services (Hicke et al., 2012; Kurz et al., 2008). Survey-based descriptions of disturbances typically only partially describe the spatiotemporal dynamics of insect and disease disturbance, particularly when surveys follow a sampling approach. Time series of wall-to-wall remote sensing data are complementary to surveys in this regard and are used to monitoring different forest disturbance types, most notably fires (Chuvieco et al., 2019) and harvest (Zhao et al., 2022). Using them to monitor insect and disease disturbances is more challenging, in part because of the lack of high-quality reference data to train and evaluate algorithms with (Fernandez-Carrillo et al., 2020; Gao et al., 2020).

The general scarcity of consistent multi-country spatial databases of insect and disease disturbances hampers not only the development of remote sensing-based disturbance monitoring. It also prevents the simulation of these events in large-scale prediction tools. Earth system models still largely ignore natural disturbance process (Anderegg et al., 2020, 2022; Friedlingstein et al., 2013). Addressing this is urgent for multiple reasons. First, the future of forests as a CO_2 sink constitutes one of the greatest uncertainties in climate projections; some Earth system models predict a persistent terrestrial CO_2 sink while others have forests switching to a source before the end of the century. Second, the impact of insect and disease outbreaks extends well beyond carbon cycling, affecting also water, energy, and nutrient fluxes (Landry et al., 2016). Finally, potential amplification effects of stress factors on forest ecosystem services result in complex feedbacks with climate that still remain largely unknown (Frank et al., 2015; McDowell et al., 2020).

With this study, we help to fill the gap on consistent and spatially explicit insect and disease forest disturbance data. We collected and harmonized 676,347 records of insect- and disease-induced forest disturbance over the period of 1963–2021 into a consistent geospatial dataset. The work was carried out through a unique joint effort of scientists from 30 research institutes and forest services across Europe, coordinated by the Joint Research Centre (JRC) of the European Commission. This collaboration led to the first spatially explicit Database of European Forest Insect and Disease Disturbances, hereafter referred to as DEFID2. Data collection and harmonization were complemented by a satellite-based quantitative characterization of the disturbances with the aim of addressing some of the key limitations existing in similar databases (e.g., the afore-mentioned IDS-USDA, NFD-CFS). We believe that DEFID2 represents a substantial contribution to improving our capacity to observe, understand, and predict insect and disease disturbances in Europe and quantify their role in forest ecosystems and the services they provide.

This paper is structured as follows: in Section 2, we describe the methodology used to collect and harmonize data, the satellite-based characterization of affected forest areas, and the data access routines. Section 3 provides thematic, spatial, and temporal detail and summaries of the content of DEFID2. Section 4 highlights possible research applications that can benefit from DEFID2. Information on data and code availability is given in Section 5. Section 6 provides guidelines to DEFID2 users and Section 7 conclusions and an outlook.

2 | MATERIALS AND METHODS

2.1 | Overall methodology

The methodological framework used to develop DEFID2 encompasses a sequence of steps spanning data collection, harmonization, satellite-based characterization, and data distribution. Various steps act as filters along the process, the first of which is the DEFID2 protocol. Data contributors may possess records about insect- and disease-related forest disturbances collected, organized, and stored in different ways. The DEFID2 protocol ensures an initial level of compatibility of format and structure among the contributions (Section 2.2). Data are requested in a geographical information system (GIS) file format in which geospatial features, that is, geometries, are described by a set of predefined qualitative and quantitative attributes. Contributions are then quality-controlled and further harmonized at the JRC. As part of this step, data contributors can be asked for clarification on their data and for feedback on the harmonization (Section 2.3). To improve consistency across records and data integrity, the GIS files are ingested into a relational database management system. Existing attributes of forest disturbances are then complemented by a satellite-based characterization of damage metrics (Section 2.4). Finally, a dedicated R package was developed to facilitate data access and use (Section 2.5). In the following sections, we describe each of these stages.

2.2 | The DEFID2 protocol

Potential data providers were initially identified through an extensive survey of peer-reviewed literature for studies generating or using insect and disease disturbance records and then invited to share their data. The data collection started from a common protocol that data providers were encouraged to follow to assure an initial level of consistency. The protocol covers, among others, information on:

- *Contents and acquisition methods*: Information on the insect(s), pathogen(s), host(s), and spatial extents of the forest areas affected by biotic disturbances are requested. Damaged areas can be derived from ground surveys, visual interpretation of aerial/satellite imagery, or some form of automatic classification of remote sensing data.
- *Spatial and temporal coverage*: Records of interest fall within geographic Europe, European Russia, Northern Africa, or the Middle

East, with disturbances occurring after 1980 receiving priority as they may be suitable for comparisons with satellite observations.

- *Format*: Disturbance records can be represented as georeferenced polygons or points, with attributes of each disturbance in an associated table.
- *Descriptive attributes*: The descriptive attributes requested by the protocol were inspired by the IDS-USDA database (USDA Forest Service, 2022). To each disturbance record, four different damage symptoms can be associated (defoliation, discoloration, mortality, and dieback). Each damage symptom can be characterized by a different severity/pattern of damage, by multiple agents, and by multiple affected host tree species. Furthermore, each forest disturbance record can be associated with two climate-driven triggering factors, with silvicultural practices, and with eventual sanitary interventions.

All the attributes delivered by data providers are listed in Table 1 as DEFID2 metadata and DEFID2 core attributes.

2.3 | Quality control and harmonization

Although the DEFID2 data protocol envisions a clean and clear data structure to facilitate data compilation, queries, and analyses, some important differences persisted between contributed datasets. We therefore developed a series of data checks and harmonization steps that the JRC conducted.

First, each original dataset received was assigned a unique code consisting of the two-digit international ISO country code (ISO 3166-1 alpha-2) and a sequential number (e.g., FR-001, France, data set number one). In subsequent steps: (1) data were checked for possible errors, oversights, or gaps; (2) data providers were contacted and consulted about their contribution, (3) data were harmonized and formatted, and finally, (4) transferred to the DEFID2 data repository. Any harmonization tasks performed on a dataset were logged, using a coding system (summarized in Table S1). The DEFID2 data repository, that forms the basis of the DEFID2 database, comprises four files expressing different relations between geometries and disturbance events:

- *exact polygon*: The extent of the disturbance corresponds exactly to the coverage of the polygon geometry provided; this represents the most realistic representation of the disturbance;
- *exact point*: A point geometry located exactly within a disturbed patch;
- *substitute polygon*: The disturbance(s) occurred within the provided polygon geometry but does/do not cover its entire extent;
- *substitute point*: A point geometry with a loose spatial relation to the disturbance event.

Many reported survey dates were not the exact date of a field survey or a satellite image acquisition. Instead, they indicated a month, season, or year in which a disturbance was observed. The field "survey_date_precision" was created to indicate a period around the "survey_date," expressed by a "±" number of days (Table 1). For example, a field survey conducted throughout June 2019 is recorded as "survey_date": "2019-06-15" and "survey_date_precision": "±15 days." When the original data stated "Spring 2017," the "survey_date" was set to "2017-04-15" with "survey_date_precision": "±45 days." When a survey date was exact, the field value stated in the precision field was: "exact."

The final GIS files and corresponding attributes are stored in a relational database management system with strict structure and field typing. Transforming the data to such fully structured data facilitates data management while preserving complex relations between attributes and ensuring data integrity. A simplified Entity Diagram (ERD) of the database structure is presented in Figure 1. The two main tables of the schema are Event and Geom for disturbance events and geometries associated with these events, respectively. Note that the relationship between these events and their associated geometries is not necessarily one-to-one, meaning that an event may be associated with multiple geometries (a side effect of data contribution in multipart geometries). At the same time, multiple events may be associated with a single geometry. The latter happens, for instance, when the provided geometries delineate forest management units (*substitute polygons*) in which several disturbance events have been reported over the years.

2.4 | Satellite-based disturbance characterization

Satellite data form a unique asset when monitoring forest disturbances given their temporal and spatial consistency across the globe, providing ever finer spatial, temporal, and spectral resolution (Meigs et al., 2015; Rodman et al., 2021). DEFID2 enriches each disturbance record with complementary quantitative satellite-based information as follows (Figure 2):

1. Time series of a remotely sensed vegetation index were retrieved to characterize the temporal dynamics of affected forest ecosystems.
2. A well-established temporal segmentation algorithm was applied to describe the spectral trajectory of forest patches and derive satellite-based damage indicators.
3. Areas where insect or disease outbreaks intersect documented fire and windthrow events were flagged to identify possible interactions among multiple forest disturbances.

DEFID2 provides this information for all disturbances that (1) were recorded as *exact polygons* or *exact points*, to ensure disturbances and satellite data can be precisely overlaid, and (2) occurred after 1999, to guarantee that relatively consistent satellite imagery was available for 5 years prior to the disturbance event (Pekel et al., 2016). Calculations were performed in Google Earth Engine (GEE; Gorelick et al., 2017) and the satellite-based attributes are included in Table 2.

TABLE 1 List of descriptive metadata and core attributes included in the reconstructed DEFID2 vector data file.

Attribute name	Definition	Attribute value
Metadata		
survey_method	Data acquisition method	NULL|Aerial photointerpretation|Satellite photointerpretation|Remote sensing classification|Field surveys
country	Country of damage	Country name
dataset_code	Unique dataset identifier	ISO country code and a sequential number (e.g., FR-001)
Core attributes		
survey_date	Date of survey of damage	YYYY-MM-DD
survey_date_precision	Precision of reported survey date	±XX days|exact|MM/YYYY-MM/YYYY
severity_defoliation	Defoliation severity	NULL|1 Low (Equal or less than 50% defoliation)|2 High (More than 50% defoliation)
severity_discoloration	Discoloration severity	NULL|1 Low (Equal or less than 50% discoloration)|2 High (More than 50% discoloration)
severity_mortality	Mortality severity	NULL|1 Marginally affected (percentage of killed trees ≤20%)|2 Moderately affected (20% < percentage of killed trees ≤40%)|3 Substantially affected (40% < percentage of killed trees ≤60%)|4 Highly affected (60% < percentage of killed trees ≤80%)|5 Totally affected (80% < percentage of killed trees ≤100%)
severity_dieback	Dieback severity	NULL|1 Low (Equal or less than 50% defoliation)|2 High (More than 50% defoliation)
agents	Comma separated list of disturbance agents	*Ips typographus*, *Thaumetopoea pityocampa*, *Tomicus destruens*, etc.
hosts	Comma separated list of affected hosts	*Picea abies*, *Pinus halepensis*, *Pinus nigra*, etc.
symptom	Comma separated list of symptoms	Defoliation, discolouration, mortality, dieback
trigger_primary	Primary trigger of damage	NULL|Drought|Heatwave|Wind/Storm|Fire|Snow/Ice|Pest/Disease
trigger_primary_date	Date of primary trigger of damage	NULL|YYYY/MM/DD
trigger_secondary	Secondary trigger of damage	NULL|Drought|Heatwave|Wind/Storm|Fire|Snow/Ice|Pest/Disease
trigger_secondary_date	Date of secondary trigger of damage	NULL|YYYY
silvicultural_system	Type of silvicultural system of the damaged forest stand	NULL|Clear cut|Shelterwood|Selective logging|None
sanitary_intervention	Type of sanitary intervention	NULL|Clear cut|Shelterwood|Selective logging|None
sanitary_intervention_date	Date of sanitary intervention	NULL|YYYY-MM-DD
sanitary_intervention_date_precision	Precision of reported sanitary intervention date	+/− XX days|exact|MM/YYYY-MM/YYYY
pattern_defoliation	Pattern of defoliation damage	NULL|High-contiguous—Host type or species is >50% and the damage is contiguous|High-patchy—Host type or species is >50% and the damage is patchy (concentrated in discrete pockets or individual trees)|Low-contiguous—Host type or species is <50% and the damage is contiguous|Low-patchy—Host type or species is <50% and the damage is patchy (concentrated in discrete pockets or individual trees)
pattern_discoloration	Pattern of discoloration damage	NULL|High-contiguous—Host type or species is >50% and the damage is contiguous|High-patchy—Host type or species is >50% and the damage is patchy (concentrated in discrete pockets or individual trees)|Low-contiguous—Host type or species is <50% and the damage is contiguous|Low-patchy—Host type or species is <50% and the damage is patchy (concentrated in discrete pockets or individual trees)
pattern_mortality	Pattern of mortality damage	NULL|High-contiguous—Host type or species is >50% and the damage is contiguous|High-patchy—Host type or species is >50% and the damage is patchy (concentrated in discrete pockets or individual trees)|Low-contiguous—Host type or species is <50% and the damage is contiguous|Low-patchy—Host type or species is <50% and the damage is patchy (concentrated in discrete pockets or individual trees)

TABLE 1 (Continued)

Attribute name	Definition	Attribute value
pattern_dieback	Pattern of dieback damage	NULL|High-contiguous—Host type or species is >50% and the damage is contiguous|High-patchy—Host type or species is >50% and the damage is patchy (concentrated in discrete pockets or individual trees)|Low-contiguous—Host type or species is <50% and the damage is contiguous|Low-patchy—Host type or species is <50% and the damage is patchy (concentrated in discrete pockets or individual trees)
is_affected	Boolean indicating whether the record corresponds to a disturbance (False in case of negative example)	True (disturbance)|False (no disturbance)

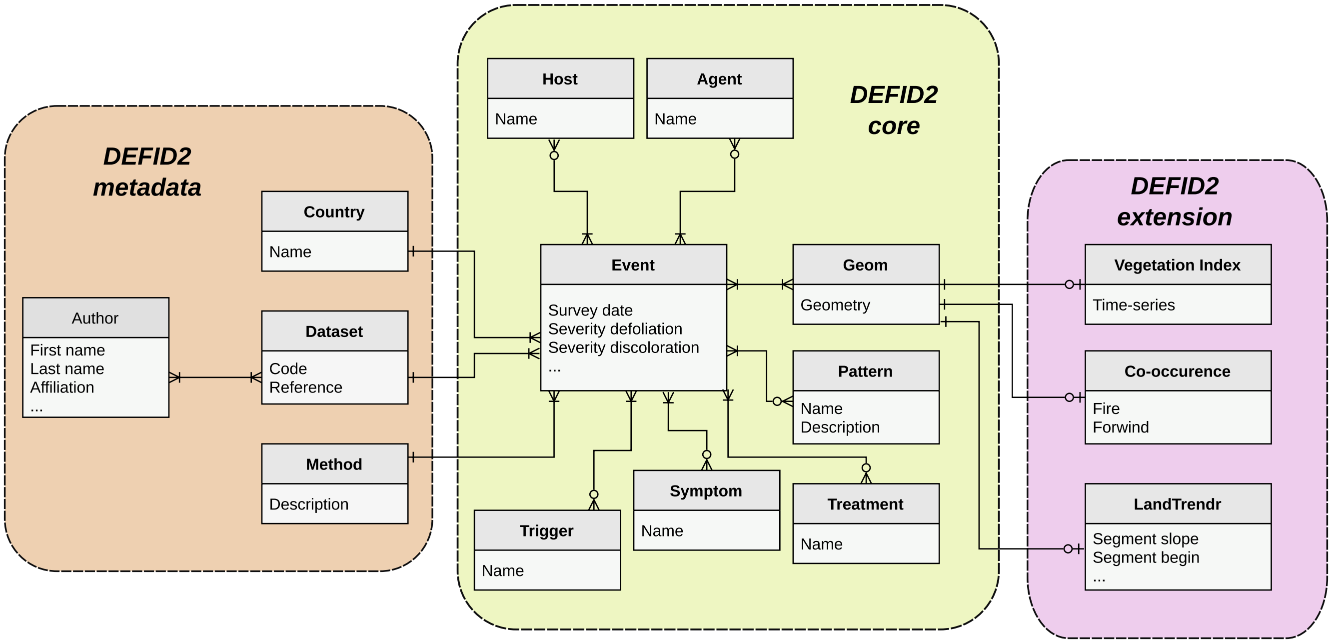

FIGURE 1 Simplified entity relation diagram (ERD) of the DEFID2 database.

The following sections detail each of the three aforementioned steps.

2.4.1 | Temporal dynamics of affected forest ecosystems

To characterize the temporal dynamics of forests affected by insect or disease disturbances, DEFID2 contains, for *exact polygon* and *exact point* records, time series of a spectral vegetation index calculated from satellite data (Figure 2a; Table 2). We used geometrically and atmospherically corrected Landsat Tier 1 Surface Reflectance imagery acquired from the United States Geological Survey from 1995 to 2021 overlapping the study area. The collection includes imagery acquired from the Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operation Land Imager (OLI). Since the TM/ETM+ and OLI sensors present reflective wavelength discrepancies, we harmonized Landsat 8 OLI bands to TM/ETM+ equivalents using slopes and intercepts from reduced major axis regression (Roy et al., 2016). We masked clouds, shadows, and snow using the CFMask-derived quality assurance band (Foga et al., 2017; Zhu & Woodcock, 2014). Areas not covered by trees according to the tree cover map for the year 2000 in the Global Forest Change (GFC) product version 1.8 (Hansen et al., 2013) were also masked during the further processing of the Landsat data. For each year and disturbance record, we produced annual medoid composites of Landsat data representative of the growing season (Flood, 2013). For the compositing, the growing season was defined locally as the 3-month period producing the highest average normalized difference vegetation index (NDVI) in the 20-year time series of the MODIS MOD13Q1 V6 Terra Vegetation Indices 16-Day Global 250 m product (Didan, 2015). The Landsat Normalized Burn Ratio (NBR) was then calculated from each annual growing season composite for the period 1995–2021. The NBR is defined as the normalized difference between Landsat TM-equivalent bands four (0.76–0.90 μm) and seven (2.09–2.35 μm) and has been extensively used in studies of insects disturbances of forests (Meigs et al., 2015; Rodman et al., 2021; Senf et al., 2017)

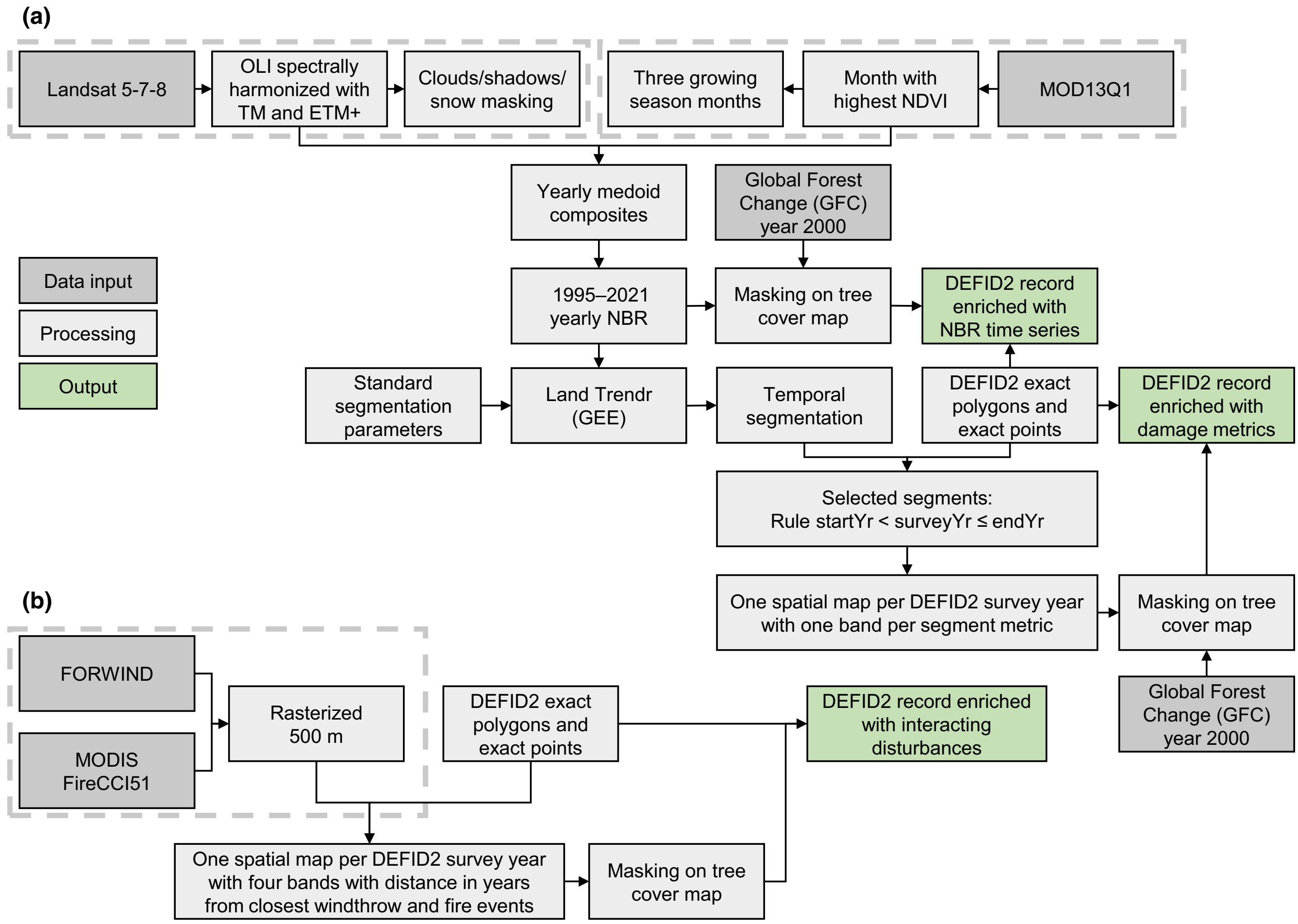

FIGURE 2 Flow chart of the satellite-based characterization of the DEFID2 records. Satellite products used include Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operation Land Imager (OLI), and MODIS MOD13Q1 V6 Terra Vegetation Indices (a). Vegetation indices used in the workflow include the normalized difference vegetation index (NDVI) and the normalized burn ratio (NBR) index. All analysis is performed in Google Earth Engine (GEE). Secondary datasets used in the workflow include the global forest change (GFC) layer, the MODIS Fire_cci v 5.1 product, and the European Forest Windthrow dataset (FORWIND) (b). Metrics derived from LandTrendr used to identify and select the spectral segments were the start year (startYr), and end year (endYr) in comparison with the survey year (surveyYr) of each DEFID2 record.

as it tends to decrease with forest disturbance and increase with forest growth (Kennedy et al., 2010). For *exact point* records, the yearly NBR medoid composites refer to the values extracted at the corresponding pixel, and for *exact polygons*, they refer to average composite values within their polygons. Estimates of spatial variance computed within the polygon are also provided for each year.

2.4.2 | Satellite-based damage indicators

To quantify the damage due to insect and disease outbreaks, we applied the Landsat-based detection of Trends in Disturbance and Recovery algorithm, LandTrendr (Kennedy et al., 2010; Figure 2a). LandTrendr is an established pixel-based temporal segmentation algorithm that extracts spectral trajectories (segments) of land surface change from yearly Landsat time series (LTS). It models a pixel's spectral time series as a sequence of segments, considered as durable spectral trajectories of change or stability separated by breakpoints. A set of metrics are then extracted for each segment, including the start value and start year, the end value and end year, the magnitude, the duration, and the slope.

The LandTrendr algorithm was applied to the NBR time series of each 30 m pixel coinciding with a DEFID2 forest disturbance record. We ran the LandTrendr version implemented in Google Earth Engine with the standard set of segmentation parameters (Kennedy et al., 2018) and without any filtering based on the minimum mapping unit or segments metric (Rodman et al., 2021; Senf & Seidl, 2021). From each pixel's LandTrendr output, we extracted the temporal segment intersecting the survey year of the DEFID2 disturbance record. When the survey year corresponded to the vertex of two LandTrendr segments, the prior segment was extracted because it is more likely to reflect the disturbance conditions at the time of the survey. For each Landsat pixel within a DEFID2 record, we derived metrics describing the short-term variations in the forest ecosystem state and provide for the extracted segment: the start year, the start value, the magnitude (defined

TABLE 2 List of satellite-based attributes included in the DEFID2 extension database. NBR stands for Normalized Burn Ratio index.

Attribute name	Definition	Unit
start_year_mode	Mode of the start year of declining spectral trajectories within the record	Year
start_value_median	Median of the start value of declining spectral trajectories within the record	NBR*1000 (NBR is dimensionless)
magnitude_median	Median of the magnitude of change of declining spectral trajectories within the record	NBR*1000 delta (NBR is dimensionless)
duration_median	Median of the duration in years of declining spectral trajectories within the record	Years
slope_median	Median of the rate of declining spectral trajectories within the record	(NBR*1000)/dur, years-1
proportion_negative_segments	Percentage of area of the record with a declining spectral trajectory in vegetation at the time of the survey	percentage
time_series	Time series of spatial average and spatial variance of yearly NBR medoid composites within the record	NBR (NBR is dimensionless)
delta_forwind_anterior	Median of the distance in years from the identified preceding (or concurrent) windthrow events within the record	Years
delta_forwind_posterior	Median of the distance in years from the identified following windthrow events within the record	Years
delta_fire_anterior	Median of the distance in years from the identified preceding (or concurrent) fire events within the record	Years
delta_fire_posterior	Median of the distance in years from the identified following fire events within the record	Years

TABLE 3 Statistics of insect and disease disturbance records collected in the DEFID2 database aggregated at country level.

	Number of records						
Country	Exact polygon	Exact point	Substitute point	Substitute polygon	Total area (ha)	Median record area (ha)	Standard deviation (ha)
Czechia	608,443				73,539	0.03	0.6
Finland	4				48	11.75	6.9
Italy	2531	1092			498,091	14.64	1428.5
Romania	1664				17,282	0.17	118.3
Slovakia	19,784				1961	0.02	0.4
Spain	34	168	33,670		47	0.55	1.8
Sweden	355				1479	3.91	3.5
Switzerland				8602			
Total	632,815 (94%)	1260 (0.2%)	33,670 (5.0%)	8602 (1.3%)			

Note: Affected area statistics include only event-geometry pairs with exact polygon relations.

as the difference between the end value and the start value), the duration (defined as the difference between the end year and the start year), and the rate (defined as the ratio between the magnitude and the duration). Note that the NBR is typically multiplied by 1000, and the derived metrics (start value and magnitude) include this scaling factor.

The LandTrendr implementation generated, for each survey year from 2000 onward, maps of metrics of the NBR time-series segments. The maps were masked based on the tree cover map for the year 2000 derived from the GFC product version 1.8 (Hansen et al., 2013) and aggregated at the record level to provide quantitative attributes for DEFID2 record and minimize the influence of any non-forest areas. The following LandTrendr-based attributes were added to the DEFID2 *exact polygon* and *exact point* records (Table 2): percentage of the area of the record with declining NBR; mode of the start year of declining NBR trajectories within the record; median of the starting value of declining NBR trajectories within the record; median of the length in years of the declining NBR trajectories within the record; and median of the rate of decline of the NBR trajectories within the record.

2.4.3 | Interactions among multiple forest disturbances

As a final step in generating supplementary quantitative information to DEFID2, we intersected insect and disease disturbances with known fire and windthrow events (Figure 2b). This information is potentially relevant to explore interactions among multiple forest disturbances.

Fire events were obtained from the MODIS Fire_cci v 5.1 product (https://geogra.uah.es/fire_cci/firecci51.php) which reports burned pixels globally at 250 m spatial resolution and at monthly temporal scale for the period 2001–2020 (Pettinari et al., 2021). This dataset includes the day of the first detection of the fire and the confidence level of the detection for each pixel. The MODIS Fire_cci v 5.1 data were masked to retain only pixels with a confidence level higher than 80%. The MODIS Fire_cci v 5.1 monthly maps were then transformed into yearly products to record for each burned pixel the year of fire detection. Data on windthrows were obtained from the European Forest Windthrow dataset (FORWIND, https://doi.org/10.6084/m9.figshare.9555008) that delineates more than 80,000 forest areas in Europe that were disturbed by wind in the period 2000–2018 (Forzieri et al., 2020). The FORWIND data were rasterized and resampled, along with the fire datasets, to 500 m spatial resolution to account for the potential spread of infestations beyond their original location. For each *exact polygon* and *exact point* record in DEFID2, we identified the known windthrow and fire events that occurred at the same location, and registered the last one preceding the survey year, and the first one during or after the survey year. This operation was performed at 30 m pixel scale and with the same masking of areas not covered by trees based on the GFC 2000 tree cover map (Hansen et al., 2013). The information was then aggregated at the record level by taking the median of the years assigned to the pixels (Table 2).

2.5 | Data access

From the DEFID2 relational database management system at the JRC, we extracted a file database (sqlite) and reconstructed a geospatial vector file in geopackage format. Both the sqlite and geopackage files are publicly available via the JRC open data repository and users can either directly download them or access them via a dedicated software package in the R programming language. In addition to being stored on the JRC open data repository, the DEFID2 datasets will be indexed with appropriate keywords in the JRC Data Catalog (https://data.jrc.ec.europa.eu/). That step ensures that data can be efficiently discovered, allows us to provide additional background information around the data and establishes proper attribution for use in subsequent research work. The defid2R R package developed for DEFID2 is published under an open-source license and maintained by the JRC at https://jrc-forest.pages.code.europa.eu/defid2r/. Because data volumes are large and the data structure complex, providing such a package greatly facilitates the handling and analysis of the data and makes DEFID2 accessible to a wider community. The defid2R package signals users when updates to the DEFID2 database are eventually available and contains bespoke functions to query and summarize the data.

3 | DATA RECORDS

3.1 | Spatial, temporal, and typological variations of disturbance occurrences

The DEFID2 database is the final output of the data collection and satellite-based characterization. The current release includes insect and disease disturbances that occurred in Czechia, Finland, Italy, Romania, Slovakia, Spain, Sweden, and Switzerland. Overall, DEFID2 currently includes 676,347 records collected by 20 research institutes and forestry services across Europe over the period 1963–2021. The records were predominantly derived from satellite/aerial photointerpretation and remote sensing data classification (ca. 93.1% of the total records, Table S2). Most data were provided as *exact polygons* (ca. 93.5%, Table 3) with fewer *substitute points* (ca. 5.0%), *substitute polygons* (1.3%), and *exact points* (ca. 0.2%). Altogether, the DEFID2 records comprise a combined forest area of 592,447 ha disturbed by insects or disease, with a median forest disturbance patch of 0.03 ha (Table 3). However, there is substantial variability between the data sets contributed to DEFID2 driven by the high heterogeneity of forest and landscape characteristics and the variety of acquisition methods employed. Figure 3 shows two examples of insect outbreaks recorded in Romania and Slovakia in the periods 2014–2017 and 2005–2009, respectively, and stored in DEFID2 as *exact polygons*.

Figure 4 shows the spatial and temporal variation among records in the DEFID2 database. To better visualize the data, we counted the number of disturbance events in hexagons on an approximate 0.5° grid in 5-year periods; most records (98%) were collected in Czechia, Slovakia, and Spain, and 96.9% of the records fall in the period 2010–2021. We point out that the above-described spatial and temporal variations of insect and disease disturbances do of course not represent the European distribution of forest insect and disease disturbances. Instead, they reflect the state of data contributed to DEFID2 thus far and contained in its first release.

All records in DEFID2 are complemented with information on the dominant agent, host, and symptom of the disturbance event, as they are key attributes requested for the database (Figure 5). Attributes related to the severity field are included in 98.6% of the records, whereas descriptions of triggers and patterns (spatial heterogeneity of disturbance) are scarcer (5.3% and 5.4% of records, respectively). Most records in DEFID2—609,500 occurrences, corresponding to 93.1% of the entire dataset—are disturbances by *Ips typographus* (Figure 6). Forest disturbances caused by *Thaumetopoea pityocampa* follow with 16,810 occurrences, which is 2.6% of the dataset. Remaining records are mostly attributed to *Tomicus destruens*, *Viscum album*, *Sirococcus conigenus*, *Gymnosporangiu* sp., *Thyriopsis halepensis*, *Zeiraphera diniana*, and *Coleophora laricella*. The near totality of disturbances caused by *Ips typographus* occurred on *Picea abies* (93.4% of the total number of records; Figure 7). Other tree species commonly affected by insect and disease disturbances in DEFID2 include *Pinus halepensis*, *Pinus nigra*, *Pinus sylvestris*, *Juniperus oxycedrus*, *Larix decidua*, *Pinus pinaster*, *Quercus ilex*, and *Abies alba*.

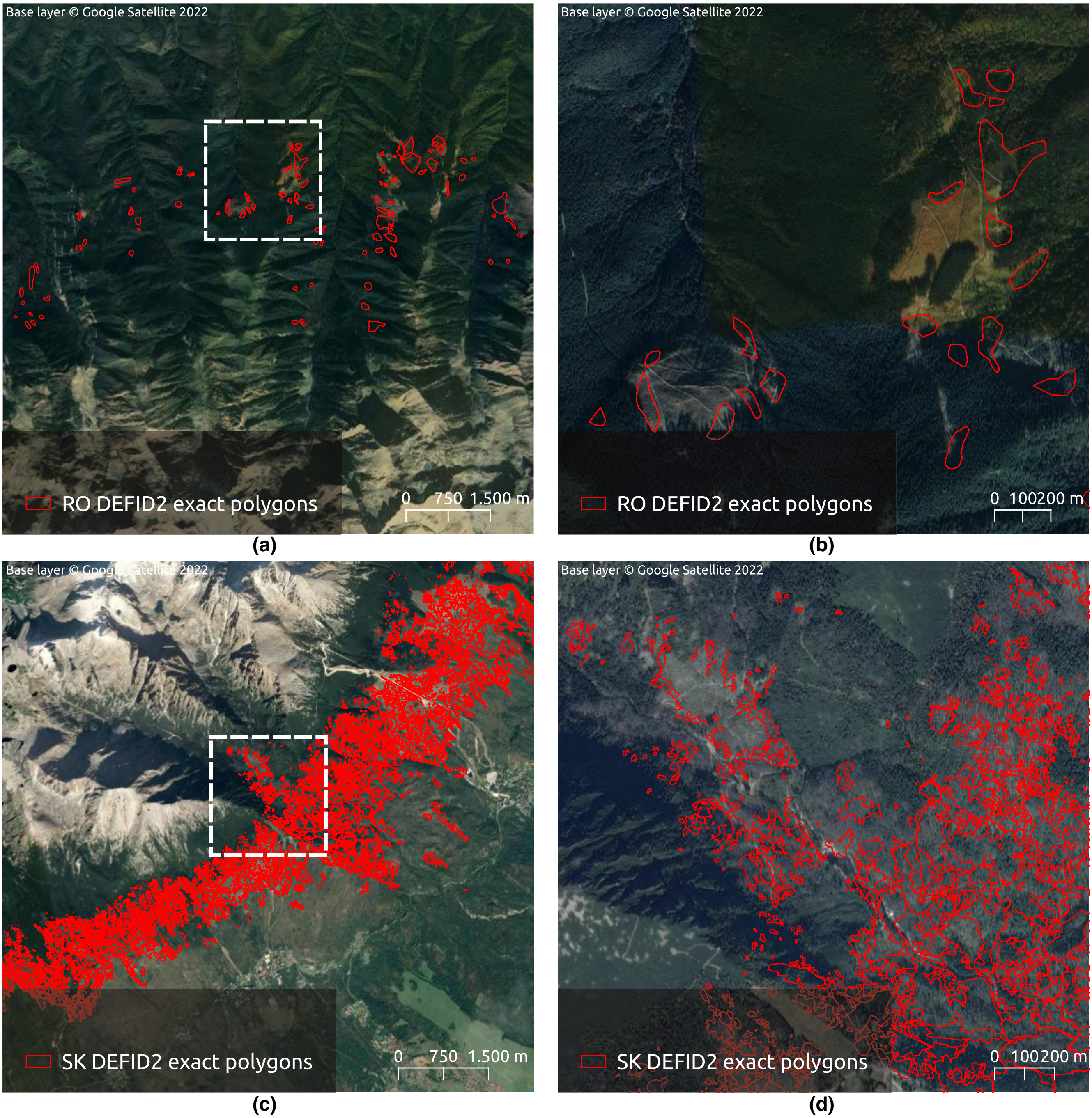

FIGURE 3 Examples of insect disturbances recorded in the DEFID2 database. (a, b) Forest area in the Făgăraș Mountains, Southern Carpathians, Brașov and Sibiu districts, Romania (RO), affected by insect outbreaks surveyed over the period 2014–2017. (c, d) Tatra Mountains in Poprad district, Slovakia (SK), affected by insect outbreaks surveyed over the period 2005–2009. Zoomed-in plots in (b, d) depict the area in the white boxes in (a, c).

3.2 | Quantitative characterization of insect and disease outbreaks from space

As highlighted in the previous sections, a series of remote sensing data processing steps were leveraged to cope with the existing limitations of survey-based database. To characterize the full temporal evolution of the forest ecosystem within a record, the time series of NBR was computed at record level. Figure 8 shows two examples of forest areas affected by insect disturbances in Romania and Slovakia surveyed in 2013 and 2008, respectively. The analysis of NBR time series can provide additional insights into forest ecosystem responses to insect and disease disturbances. They also provide a clearer picture of the temporal evolution of the forest, including the predisturbance dynamics and the post-disturbance recovery or any post-disturbance forest management implemented, such as a clear-cuts in the Romania example (Duduman et al., 2022),

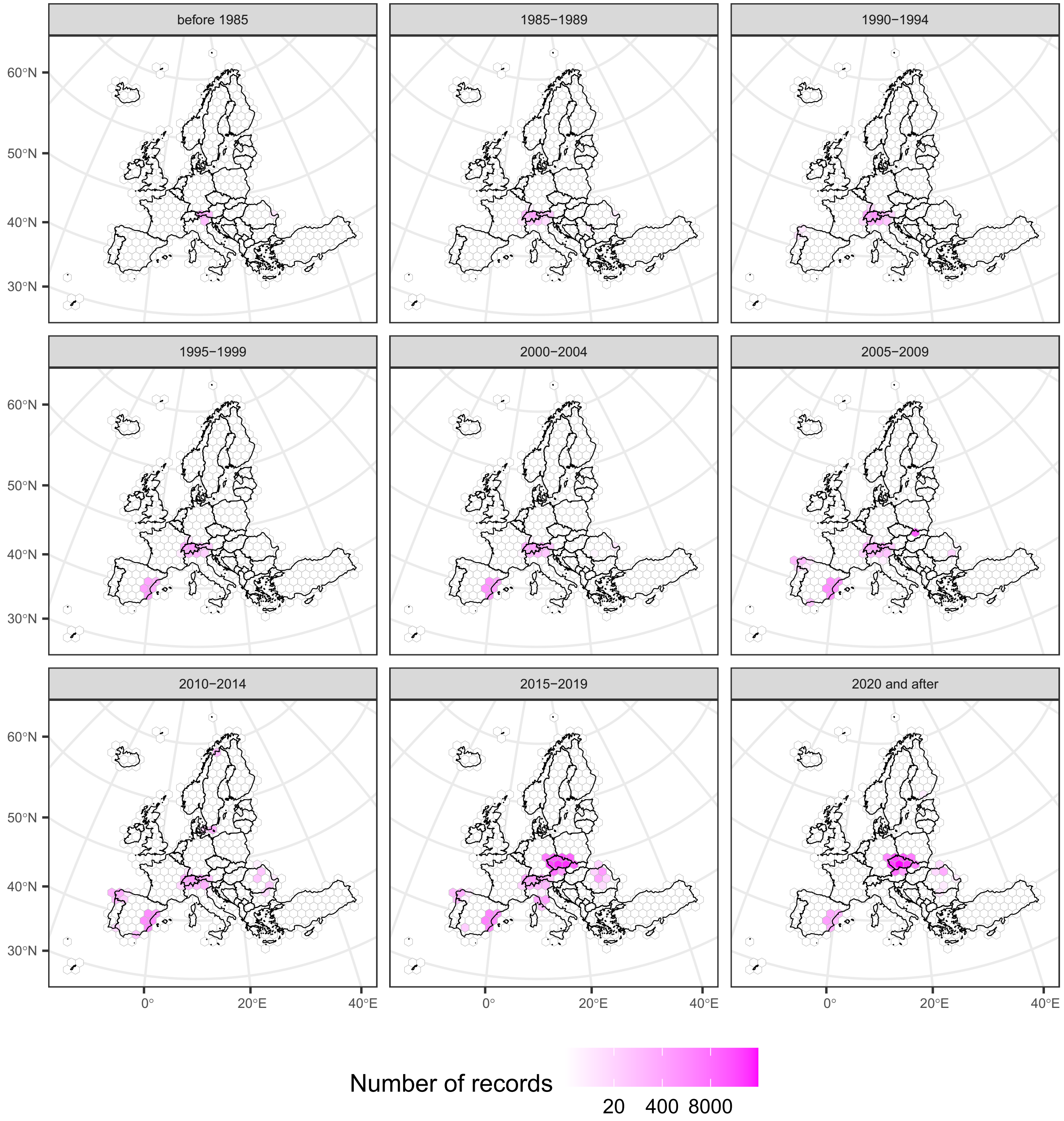

FIGURE 4 Spatio-temporal distribution of forest disturbance records contributed to DEFID2. Each hexagonal bin represents an area of about 20,000 km^2 and values are shown for 5-year temporal windows. Note the logarithmic color gradient used to better visualize the unbalanced density distribution. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

which is a common practice across Europe. Such information is helpful, for instance, to estimate the time it takes for the canopy cover to fully recover predisturbance conditions (Senf & Seidl, 2022), often referred as forest resilience (Nikinmaa et al., 2020).

Figure 9 shows key metrics of the spectral trajectories identified in disturbed forest patches as retrieved using the LandTrendr algorithm. The area is a forest in Romania affected by bark beetle disturbances and surveyed in 2013. It illustrates how forest patches delineated by the surveys are not homogeneously affected by insect disturbance (Meigs et al., 2015; Olenici et al., 2022). Within the same DEFID2 record, only a portion of the forest may have been attacked, as indicated by a negative slope or magnitude (here multiplied by 1000) of the NBR trajectory (Figure 9c,d). The satellite data also indicate that the insect outbreak started at different times within

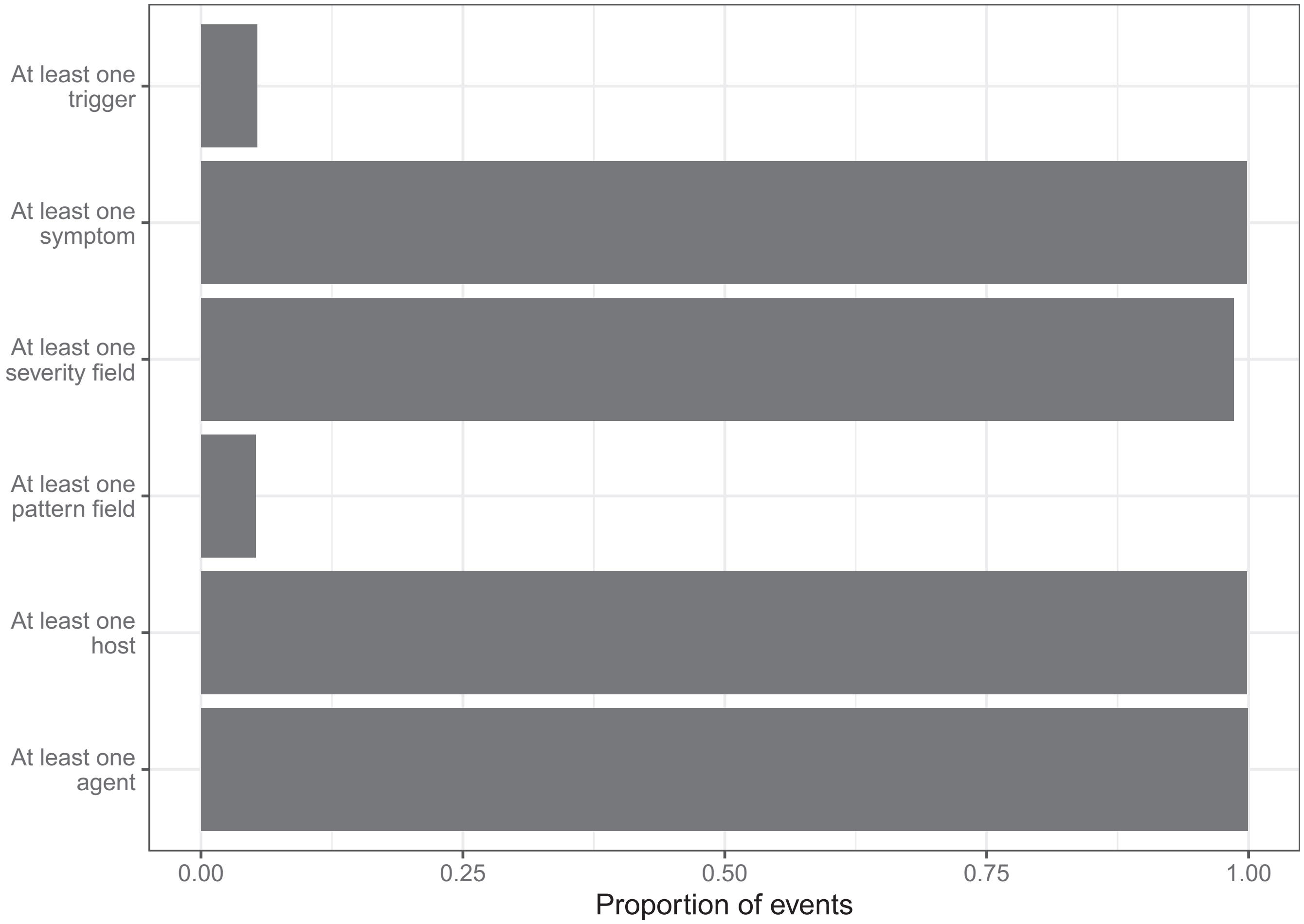

FIGURE 5 Attribute completeness of data contributed to the DEFID2 database. Note that given the large volume of records from Czechia (Figure 4), the proportions largely reflect the status of that dataset.

the same affected patch (Figure 9a) and had different durations (Figure 9b), revealing spatiotemporal variation in insect disturbance impacts (Meigs et al., 2015).

Figure 10 shows record level damage metrics binned as a function of annual average precipitation and temperature over the 1970–2000 period derived from the WorldClim dataset (Fick & Hijmans, 2017). Most of the *exact polygon* records fall around 600 mm annual precipitation and 8°C average temperature, which in Europe represents relatively warm and dry conditions. Previous studies have documented that high average temperatures and water stress are key drivers of forest vulnerability to insect and disease outbreaks possibly because they reduce plant resistance to pest damage (Forzieri et al., 2021; McDowell et al., 2011). Moreover, warm and dry weather anomalies may accelerate insect growth and population dynamics and reduce mortality rate in pest populations. More severe disturbance, here expressed in terms of magnitude, slope, and duration of the NBR change occurring during insect and disease outbreaks, appear associated with temperatures between 6°C and 10°C and lower precipitation amounts (<800 mm). However, comparable damage metrics are also found for milder temperatures and higher precipitation values. Such patterns may potentially reflect larger damages in high biomass stands, which typically grow in wetter conditions. We stress that the database does not provide a comprehensive picture of the overall disturbances occurred in European forests and therefore the full frequency distribution of disturbances and the corresponding damage metrics could deviate from those ones sampled in DEFID2 and represented here in climate spaces. Nevertheless, we highlight that the collected records cover a wide range of climate conditions representative of most European forest types. Altogether, results shown in Figures 9 and 10 provide an example of how satellite-based estimates of damage metrics produced in DEFID2 can serve to consistently compare spatiotemporal characteristics of insect and disease disturbances regardless of their acquisition methods.

DEFID2 also indicates whether forests were affected by known wildfires or windthrow events before or after an insect or disease outbreak. Figure 11 shows an example from the Tatra Mountains in Slovakia. The region was severely affected by a windstorm in 2004 that damaged 12,000 ha of forest, mostly consisting of Norway spruce. In the protected areas, about 165,000 m^3 of damaged wood was left uncleared (Nikolov et al., 2014). These uncleared sites triggered a spruce bark beetle (*Ips typographus*) outbreak that propagated rapidly from the wind-affected damaged trees. It illustrates

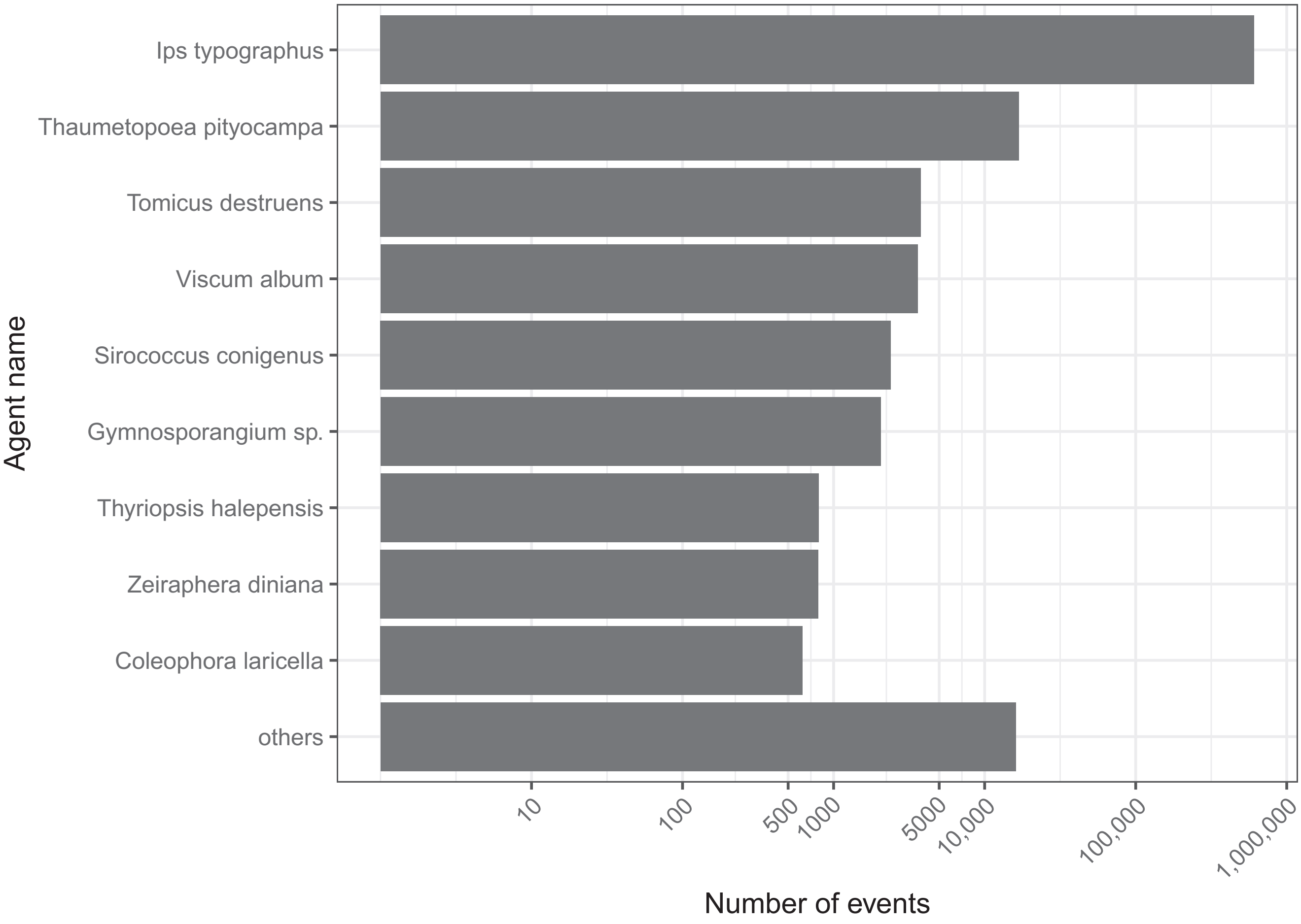

FIGURE 6 Overview of disturbance agents in the DEFID2 database.

how natural forest disturbances can exacerbate each other through interlinkages at different spatial and temporal scales (Sturtevant & Fortin, 2021). Uprooted and broken trees, as those felled by the strong winds over the Tatra Mountains, are virtually defenseless against bark beetles and provide readily available breeding material that promotes the buildup of beetle populations and the consequent increase in insect disturbance (Seidl et al., 2017; Stadelmann et al., 2014). Bark beetle infestations triggered by significant windthrow episodes may transition from windthrow-driven to patch-driven outbreak dynamics (Økland et al., 2016). In the first 3 years after the windthrow, the infestation patches in the Tatra Mountains were predominantly initiated by beetles that hatched in the windthrown substrate. After this became exhausted or unsuitable for breeding, beetles that developed in new infestation patches became the main driver of further attacks. In turn, insect outbreaks, and specifically the trees they kill, can increase the severity and spread of subsequent forest fires by increasing flammability and fuel (Meigs et al., 2016). The magnitude of these interactions varies with insect type and timing. Therefore, as changes in the climate system are conducive to an intensification of disturbance regimes, compound effects originating from multiple disturbance interactions can be expected to become more prevalent as well (Seidl et al., 2014; Westerling et al., 2011; Zscheischler et al., 2018). Such cascading and amplification effects originating from natural disturbance interactions can increase the vulnerability of forest ecosystems and ultimately lead to irreversible shifts in ecosystem states (Seidl et al., 2016).

DEFID2 counts 10,032 records preceded by a windthrow event, and 217 records followed by one. It counts 481 records preceded by a fire event, and five records followed one (Figure 12). The frequency distribution of the relation windthrow → insect/disease disturbance (insect/disease disturbance following a windthrow, Figure 12a) shows that prominent interactions occurred at temporal lags shorter than 6 years. The relation fire → insect/disease disturbance (insect/disease disturbance following a fire, Figure 12c) shows two distinct peaks in the frequency distribution corresponding to lags 3 and 9 years. Less evident patterns emerge in the relations between insect/disease → windthrow/fire disturbance (windthrow/fire disturbance following an insect/disease disturbance, Figure 12b,d). We point out that the estimated lags can be potentially subject to different sources of uncertainty. First, remote sensing retrievals of insect and disease outbreaks may miss the exact timing of the disturbance. This can originate for instance from a lack of cloud-free images used as input in classification algorithms, or from the complexity to detect the onset of insect and disease disturbances very often manifested in tiny changes in vegetation's spectral properties.

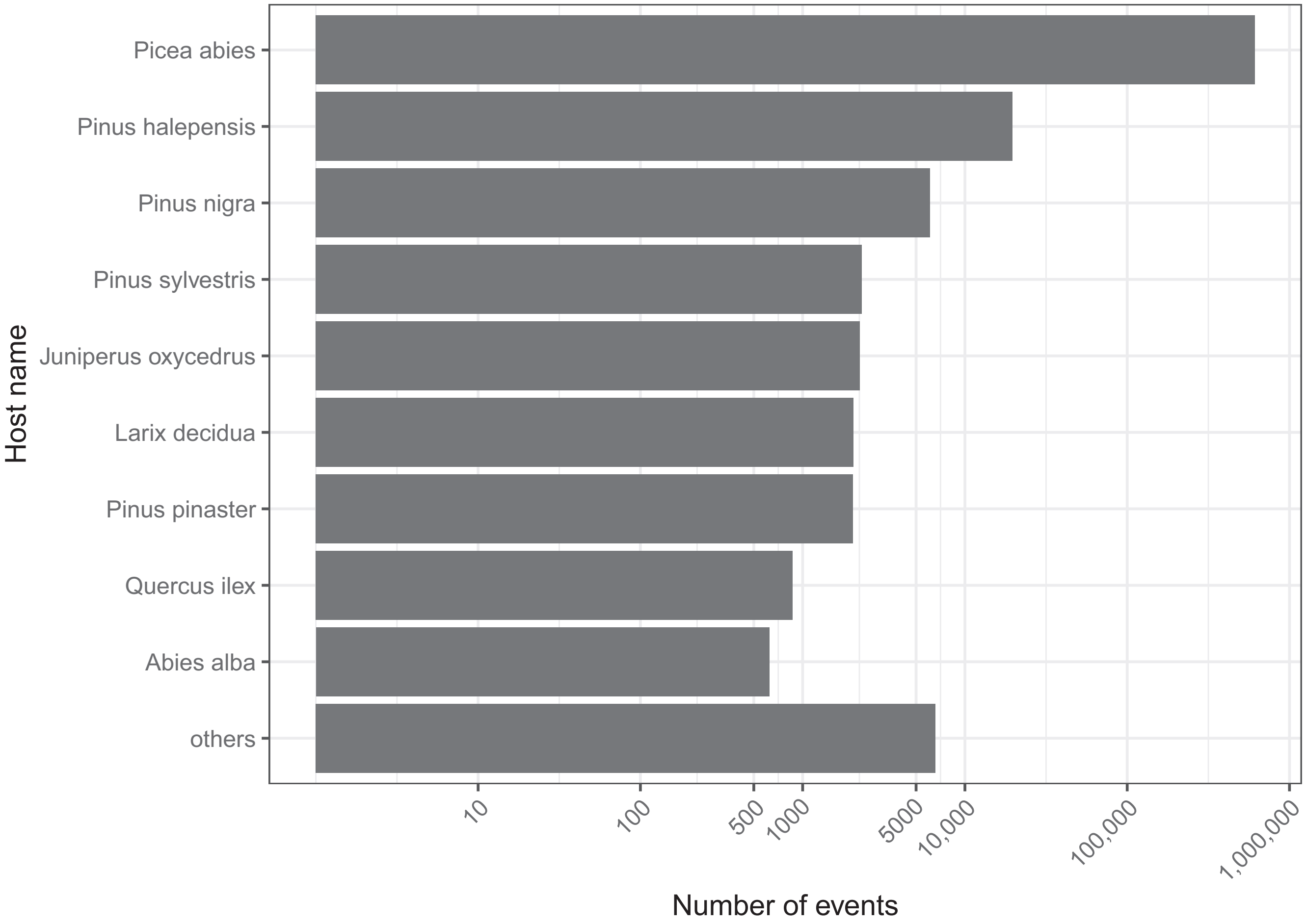

FIGURE 7 Overview of host species in the DEFID2 database.

These uncertainties in principle hold not only for DEFID2 but also for the remote sensing retrievals of fires and windthrows incorporated in the MODIS (Pettinari et al., 2021) and FORWIND (Forzieri et al., 2020) datasets used here. Second, forest management, not explicitly considered in this experiment, might have played a role in the interactions between the occurrence of multiple natural disturbances. For instance, increased fragmentation of forests could have likely reduced the horizontal spread of single disturbances (Jactel et al., 2009) and therefore the likelihood of spatial interdependences of multiple disturbances. However, the lack of spatial consistent maps of forest management hampered the integration of these effects in our assessment. Third, the estimated lags reflect the temporal distance of two different natural disturbances occurring in the same forest area, regardless of the magnitude of the single events. However, the interaction between multiple disturbances can also be severity dependent. For example, a forest area largely affected by uprooted trees due to strong winds can provide enormous defenseless breeding material to support the buildup of beetle populations (Stadelmann et al., 2014) with a much higher probability of triggering insect outbreaks compared to areas with less severe wind storms. Therefore, the interactions among multiple forest disturbances reported in DEFID2 should be considered in view of these uncertainties.

4 | POSSIBLE APPLICATIONS OF THE DEFID2 DATABASE

The following sections describe four possible applications of the DEFID2 database. The selected topics should not be intended as an exhaustive overview of the possible uses of DEFID2 but represent frontier research applications directed at increasing the resilience and long-term stability of global forests. For such applications, DEFID2 could help enhance our ability to observe, understand, and predict forest disturbances and their impact on the biosphere at large scales.

4.1 | Optimizing the use and reuse of disturbance records collected through a range of methods

Reference data on pest occurrences are crucial to address key knowledge gaps in insect and disease ecology. However, generating them is time consuming and requires expertise on each group of agents. Networks that adopt common approaches and designs to collect data or conduct experiments at international scale, for example, concerning wood borers (Roques et al., 2023) and fungal pathogens (Paap et al., 2022), can be extremely valuable in this regard. Newer approaches to collect

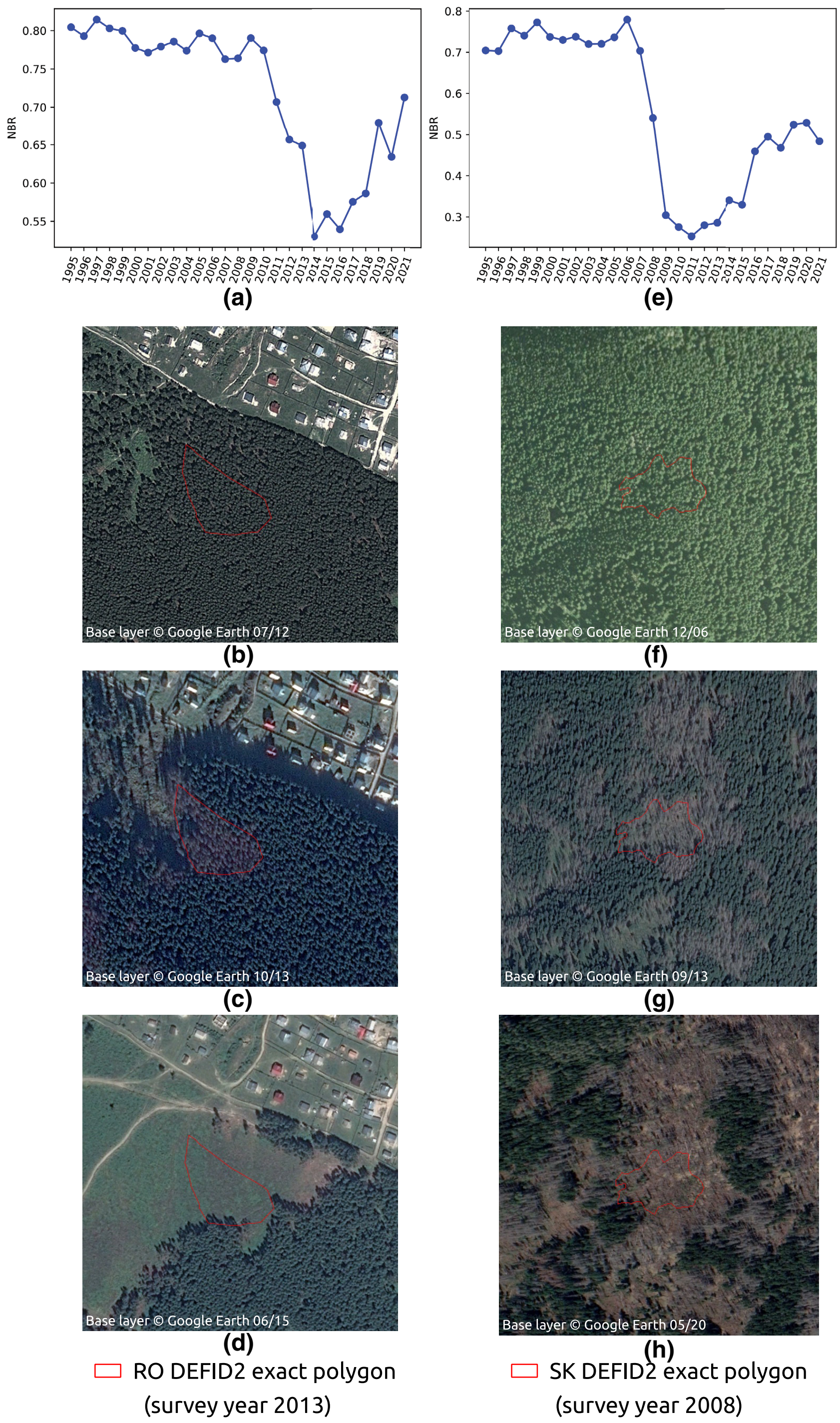

FIGURE 8 Examples of satellite-based forest dynamics in areas affected by insect disturbances. Annual changes in satellite normalized burn ratio index (NBR) over forest areas located nearby the town of Mironu in Suceava district, Romania (RO) (a), and nearby the town of Podbanské in Tatra Mountains in Poprad district, Slovakia (SK) (e), affected by insect outbreaks surveyed in 2013 and 2008, respectively. Satellite imagery shown in (b–d) and in (f–h) clearly displays the changes in forest cover during the outbreaks for the two case studies considered.

pest occurrence data include citizen and participatory science and crowd sourcing platforms (de Groot et al., 2023). The potential of digital technologies to improve detection of pests is enormous, particularly when they are matched to stakeholder needs and improve efficiency compared to more traditional approaches. Smart traps that are able to recognize insects attracted by specific lures, based on their image or movement, and remote monitoring is flourishing in several fields (Preti et al., 2021) and robot systems combining visual and molecular identification are available (Wührl et al., 2022).

DEFID2 brings together geospatial data on insect and disease disturbance in forests and facilitates their use. It already hosts data collected through field inventories as well as remote sensing, and in the future could accommodate data collected through other approaches too. This flexibility to provide access to datasets of varying nature helps ensure that DEFID2 can incorporate datasets generated through novel methods in the future. Users of DEFID2 should be aware that data in the database were generated through a range of methods, and were standardized a posteriori. Hence, the entirety of the records in

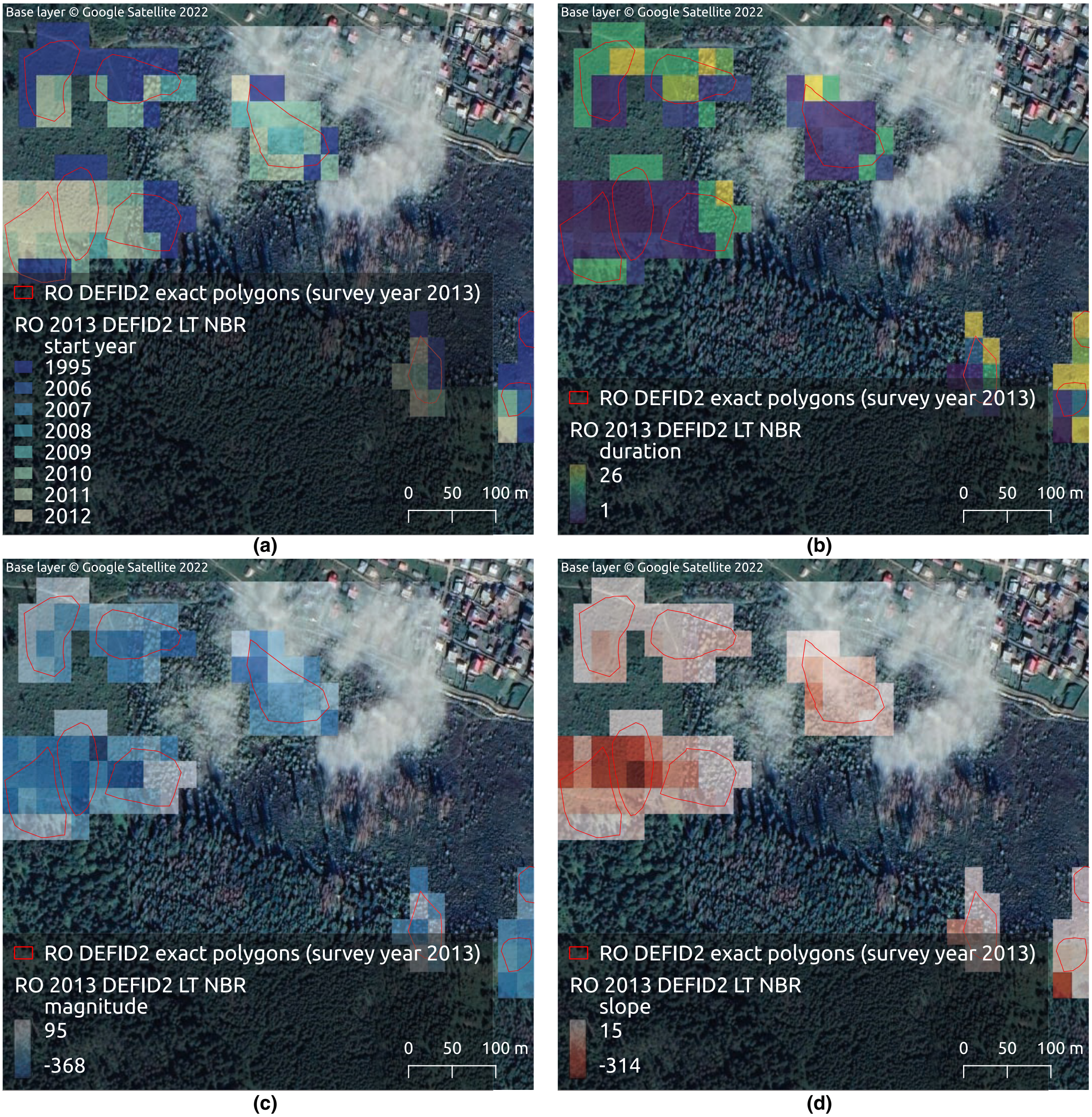

FIGURE 9 Example of four key metrics describing the spectral trajectories identified in the DEFID2 disturbance records as retrieved using the LandTrendr algorithm. The outbreak occurred near the town of Mironu in Suceava district, Romania (RO) and was surveyed in 2013 (red lines on the map). Displayed metrics are start year (a), duration (years) (b), magnitude of change (c), and slope of the trends (d) measured over the DEFID2 records.

DEFID2 should never be considered as standardized monitoring data. However, given the wide-ranging impact of biotic forest disturbances, there are calls for countries to harmonize their regulations regarding the application of monitoring methods and rapidly share detection data to improve continent-wide monitoring (Nahrung et al., 2023). In this regard, by providing examples of existing ground and remote sensing-based records, DEFID2 can inform future initiatives that aim to create standardized monitoring schemes.

4.2 | Large-scale monitoring systems of insect and disease disturbances

Terrestrial disturbances are accelerating globally, but their full impact is not quantified because we lack adequate monitoring systems (McDowell et al., 2015). Important progress has been made on the global detection of forest disturbances through remote sensing, and specifically time-series analysis of Landsat

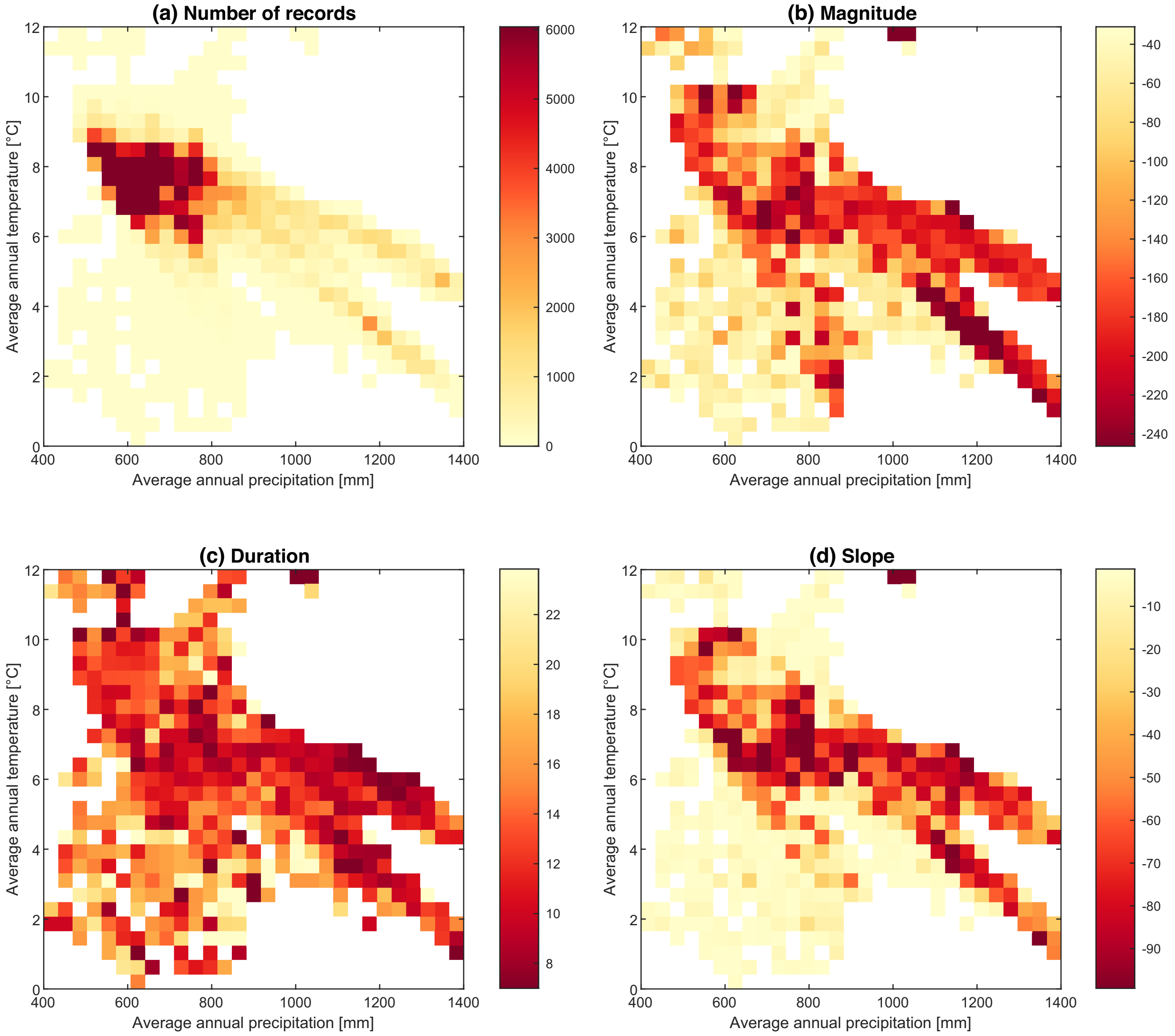

FIGURE 10 Distribution of sampled damage metrics in the DEFID2 database across climate gradients. Number of records (a), magnitude (b), duration (years) (c), and slope (d) of the declining trends associated with insect and disease disturbances recorded in DEFID2 and binned as a function of annual average precipitation and temperature computed over the 1970–2000 period from the WorldClim dataset (Fick & Hijmans, 2017).

and MODIS images (Hansen et al., 2013; Mildrexler et al., 2009). However, attributing disturbance causes through remote sensing data remains challenging (Gao et al., 2020; McDowell et al., 2015). While distinguishing major human-induced disturbances from fires is now feasible, classifying other natural disturbances such as insect outbreaks and windthrows has not yet been achieved at large scales (Curtis et al., 2018).

Remote sensing observations on sparse plot studies have provided important insights into the spectral, temporal, and spatial characteristics of several disturbance types. For example, the spectral response following fires reflects a mixture of dead and burned material and exposed soil (Kennedy et al., 2012; Zhu et al., 2012). Disturbance types can have diagnostic temporal signatures too; bark beetle-caused infestations typically first cause needle discoloration, followed by needle loss (Meigs et al., 2011). Temporal sequences of spectral indices have been used to characterize disturbance events, such as logging, fire, and insect outbreaks (Coppin et al., 2004; Kennedy et al., 2007). Different agents of change may also present distinct spatial signatures. For example, forest disturbances from insect outbreaks usually display an amorphous spatial structure and an irregular degree of damage (Coops et al., 2010). By contrast, areas damaged by windthrows caused by tornadoes typically have an elongated geometry, oriented along the path of travel of the tornado (Bech et al., 2009). Spectral, temporal, and spatial patterns of disturbances can thus be informative to attribute the cause of the disturbance.

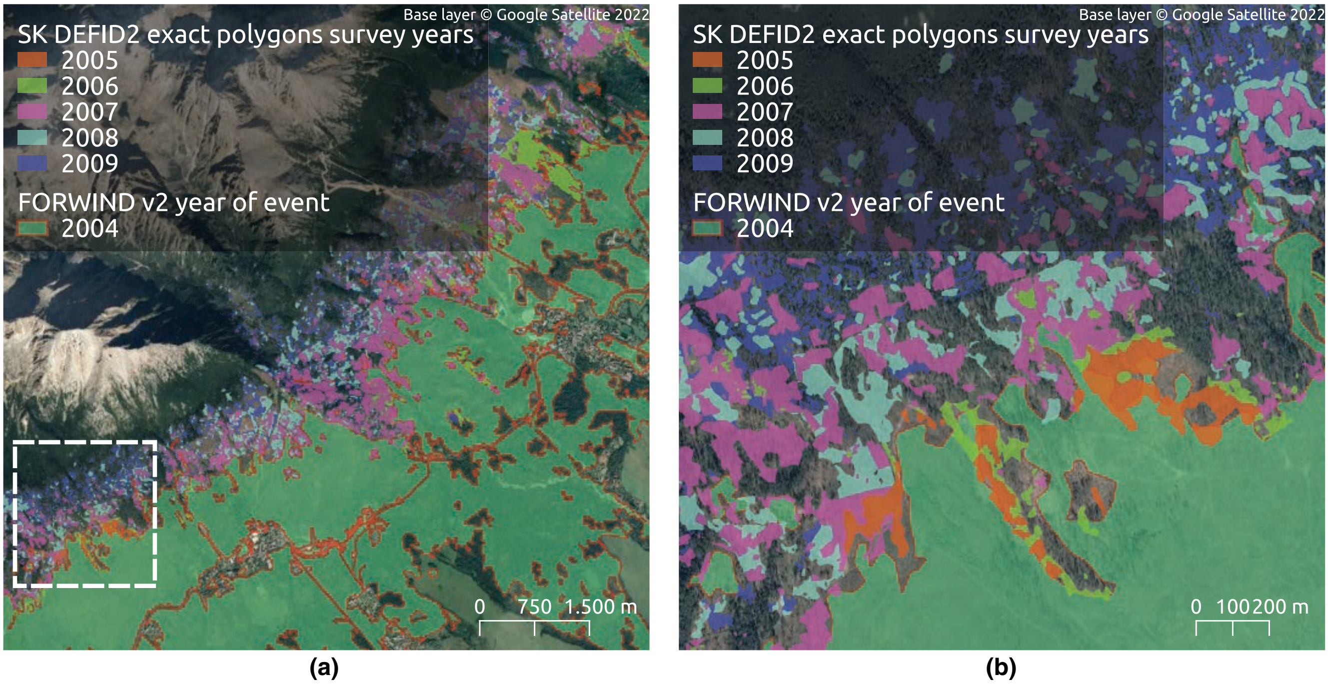

FIGURE 11 Example of multi-disturbance interactions recorded in the DEFID2 database. Insect outbreaks in the Tatra Mountains in Poprad district, Slovakia (SK), surveyed during the period 2005–2009, occurred after the wind disturbance event recorded in 2004 in the FORWIND database (Forzieri et al., 2020). Panel (b) shows the area outlined by a white box in (a) in greater detail.

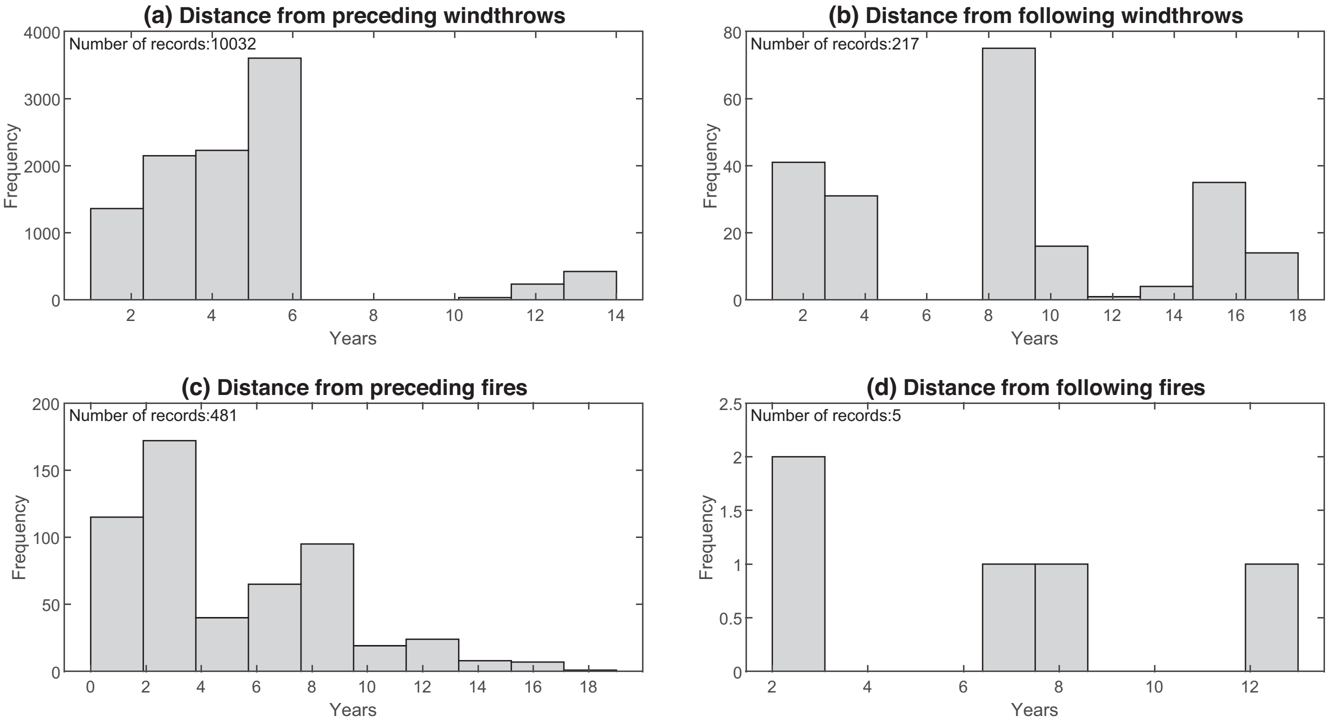

FIGURE 12 Insect or disease disturbance records in DEFID2 that happened where windthrow or fire disturbance also took places. Graphs show the frequency distribution of the time between insect and disease disturbances and preceding windthrows (a), following windthrows (b), preceding fires (c), and following fires (d). Time is measured in years, and the total number of records is included in the top left label of each panel. Windthrows and fires events were retrieved from the FORWIND database (Forzieri et al., 2020) and from the MODIS product (Pettinari et al., 2021), respectively.

The increasing availability of high-resolution satellite data, be they publicly (e.g., LANDSAT and COPERNICUS Sentinel-2 constellations) or commercially (e.g., Planet Inc.) operated (Claverie et al., 2018; Wulder et al., 2012, 2016), and the advances in cloud-based data storage and processing platforms (Gorelick et al., 2017) offer unprecedented opportunities to set up operational land cover monitoring systems at regional-to-global scales. In such a big data analytics framework, approaches based on deep learning may namely detect and map dynamic process such as biotic forest disturbances based on their spatio-spectro-temporal features and overcome some limitations in traditional classification approaches (Reichstein et al., 2019).

However, such approaches have yet to be implemented in a more automated and comprehensive fashion at regional or global scale and considering multiple types of disturbance (McDowell et al., 2015). This is in large part due to the lack of large and consistent databases of observed forest disturbances that are required to train and validate the necessary algorithms. In this regard, DEFID2 represents an important observational data source to enable the greater use of remote sensing in forest disturbance monitoring systems.

4.3 | Understanding insect and disease disturbance dynamics

Climate extremes exert strong controls on disturbance dynamics. These controls can be direct as when wind gusts lead to windthrows, or indirect, as when climate extremes generate heat or drought events that increase the susceptibility of a forest to pathogens (Lesk et al., 2017; Seidl et al., 2017). When disturbances occur, forest ecosystems can respond immediately (e.g., the loss of carbon stock during a forest fire), but also lagged in time (e.g., productivity or compositional changes after drought (Beck et al., 2011; Viljur et al., 2022; Yang et al., 2018)).

Understanding both the causal dynamics and ecosystem responses of forest disturbances requires modeling efforts as well as empirical data (McDowell et al., 2015). Compilations of gray literature reports on past mortality events can provide large spatial coverage (Gregow et al., 2017; Schelhaas et al., 2003; Seidl et al., 2014; Senf et al., 2018), but records at coarse spatial resolution (e.g., country level) mask important information on site-specific drivers and temporal dynamics of forest damage. Current geospatial databases of forest disturbances, like the IDS-USDA database of insect and disease outbreaks in the United States, in turn do not yet allow for quantitative assessment of forest damage by biotic agent.

Large collections of detailed disturbance records covering a variety of forest and climate conditions, as is the aim of DEFID2, can therefore help gain insights into the ecological and environmental processes that drive insect and disease disturbances. This will require that empirical data on disturbances are paired with environmental data, including from Earth Observation. Driving modern causal methods (e.g., causal network learning algorithms and structural causal model framework; Runge et al., 2023; Runge, Bathiany, et al., 2019; Runge, Nowack, et al., 2019), with this combination of data, could substantially advance the state of the art in understanding and quantifying complex dynamical systems of forest disturbance.

4.4 | Integrating biotic disturbances in Earth system modeling

There are signals that future warming may lead to an intensification of the forest disturbance regime in Europe (Seidl et al., 2014, 2017). Although useful, statistical approaches are unlikely to realistically extrapolate current disturbance dynamics much beyond the short observational record or to capture emerging dynamics resulting from complex feedbacks (Mack et al., 2021), especially under the rapid and drastic environmental changes expected in the coming decades. Quantifying the extent and impact of future natural disturbances on forest functioning and structure therefore requires the use of models that can fully incorporate feedbacks between global environmental and climatic changes, biotic disturbances, and forest condition (Bastos et al., 2023).

Land Surface Models (LSMs)—the land component of Earth system models used in future climate projections—can mechanistically represent biogeochemical and biophysical processes and feedbacks in coupled climate–vegetation systems (Bonan, 2008; Bonan & Doney, 2018). Some LSMs include fire disturbances (Lasslop et al., 2014; Thonicke et al., 2010; Yue et al., 2014), but other natural disturbances are typically only represented as part of background mortality rates due to our incomplete understanding of the underlying ecological processes (Bonan & Doney, 2018; Chen et al., 2018; Hantson et al., 2020; Huang et al., 2020). An explicit representation of disease and insect disturbance dynamics and physiology-based tree defense in large-scale models requires the consideration of species-specific differences in tree traits and physiology, thresholds of various agent–host systems (e.g., the number of beetles required to overcome trees defenses) and potential cross-scale amplification effects of some beetle species (Huang et al., 2020; Koven et al., 2020; Raffa et al., 2008).

Previous attempts to integrate biotic disturbances in LSMs have mostly focused on disturbance impacts of single agent–host systems and were limited in their spatial coverage (landscape to regional scales; Edburg et al., 2011; Huang et al., 2020; Kautz et al., 2018). In a pioneering study, however, multiple biotic disturbance rates were prescribed in a dynamic global vegetation model to quantify their recent impact on forest carbon dynamics in the United States (Kautz et al., 2018). If DEFID2 can extend its spatial coverage, it will enable such impact studies at the scale of the European continent.

Efforts to represent insect and disease outbreaks in LSMs have been made, but explicitly simulating biotic disturbances in LSMs is challenging due to the lack of information to parameterize these processes globally or regionally (Section 4.2), the spatial-scale mismatches (areas reported here in DEFID2 typically measure 0.03 ha, vs. LSM grid cells measuring thousands of km^2) and due to process complexity (reproduction, development, mortality, dispersal, and attack behavior of biotic disturbance agents).

DEFID2 will provide crucial information to support the development of prognostic insect disturbance models in LSMs. First, by providing new empirical insights on global key drivers of insect and disease outbreaks derivable from DEFID2 and satellite data

(Section 4.3). Second, DEFID2 can be combined with additional data on tree species, stand structural and functional diversity, landscape properties, etc., to support the development of parameterizations at the coarser resolution of LSMs. Finally, DEFID2 can be used to identify the minimum level of complexity needed to represent insect disturbance regimes and interactions with other disturbances (drought, fires) to realistically represent biotic disturbance dynamics across different agent–host systems and large environmental gradients and their feedbacks with other key processes in the Earth system.

5 | DATA AND CODE AVAILABILITY

The DEFID2 database presented in this study is freely available at https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/FOREST/DISTURBANCES/DEFID2/ and will be periodically updated with records on new or historical events. To this effect, the authors welcome further data contributions and commit to properly acknowledging them; the protocol for data contribution is available at https://forest.jrc.ec.europa.eu/en/activities/forest-and-tree-pests/. The defid2R package developed in the R programming language to facilitate data access and use is freely available, along with its documentation, at https://jrc-forest.pages.code.europa.eu/defid2r/. All Google Earth Engine scripts developed for the satellite-based characterization of the DEFID2 records are available via the same documentation.

6 | GUIDANCE FOR DEFID2 USERS

To properly exploit DEFID2 records, it is important to fully understand the limitations of the database and the tools available to use it. As highlighted in the Materials and Methods section, there is considerable heterogeneity among the records in DEFID2 because they stem from datasets collected through diverse acquisition methods (e.g., field surveys, aerial photointerpretation, remote sensing data classification) and for different purposes. Even when records are derived using the same method, they are potentially affected by the subjectivity of the different operators or research teams responsible for applying them. Indeed, no standard and shared protocols for the collection of insect and disease disturbance data exist at European level. In this study, to facilitate the interpretation and comparability of these records that are inherently heterogenous, we developed the satellite-based characterization of DEFID2 records to quantify damage metrics consistently in space and time. This represents an added value of DEFID2 compared to existing large-scale forest disturbance mapping systems that have their own degrees of heterogeneity (Canadian Forest Service, 2022; USDA Forest Service, 2022). In addition, the defid2R R package facilitates access to the database and provides functions to identify and extract records that meet a user's criteria. For example, users can filter DEFID2 for records collected by a specific acquisition method, in a particular temporal range, or with comparable damage metrics. The implemented R functions also facilitate the generation of summary statistics and figures based on the selected records.

The above-mentioned heterogeneity also leads to qualitative differences between the collected data. For instance, disturbance data acquired from remote sensing classification are likely less accurate than those derived from field surveys. However, providing harmonized estimates of data quality across DEFID2 is not feasible at this point because uncertainties depend on a variety of factors. These include the sampling schemes, equipment, and methods used during ground surveys, the types of remote sensing data analyzed, and modeling frameworks used to classify them. While this prevents quality flags from being generated for individual records, we point out that the satellite-based damage metrics included in DEFID2 and mentioned above, estimate disturbance severity and trajectories consistently across DEFID2 records contributed as *exact polygons* or *exact points*, mitigating some of the data quality differences. Furthermore, DEFID2 provides for each record information on the data provider, allowing users to directly interact with the persons/institutions responsible for the data acquisition on the data origin, quality, and usage.

DEFID2 currently provides data for eight European countries and obviously does not provide a comprehensive picture of insect and disease disturbances that occurred in Europe over the last decades. Nevertheless, the database already covers large environmental gradients representative of most European forest types (see for example Figure 10), and therefore can already serve large-scale studies of biotic disturbances. Due to its geospatial nature and relational database format, DEFID2 complements the Database on Forest Disturbances in Europe (Patacca et al., 2023; Schelhaas et al., 2003; DFDE, https://efi.int/articles/database-forest-disturbances-europe) that reports forest damages in terms of area affected and corresponding volume of biomass loss over the period 1950–2019 based on literature research. While DFDE does not necessarily reflect the effective disturbance damage incurred in Europe and is similarly subject to multiple sources of uncertainties and biases (Patacca et al., 2023), it can indicate where data collection efforts for DEFID2 could be particularly beneficial. For example, for the period between 1985 and 2021, DFDE (Patacca et al., 2023) reports bark beetle and other biotic disturbances for 17 countries; these damages comprise the greatest volume respective to the national forest area in Czechia and Slovakia (respectively, 6137 and 2223 m^3 damaged per km^2 of forest area reported in FAO (2020)), followed by Poland (1402 m^3/km^2), Austria (1317 m^3/km^2), and Slovenia (1086 m^3/km^2). For the latter three countries, DEFID2 does not contain any data yet, and data contributions could be particularly enriching. This is also the case for Germany, where DFDE reports 80 million m^3 of wood damaged to bark beetles and other biotic disturbances in the period 1985–2021, the greatest absolute volume after Czechia and Poland.

It is worthwhile emphasizing that DEFID2 constitutes a database of insect and disease disturbances and should not be confounded with a forest disturbance monitoring system. Therefore, users seeking to develop applications that can distinguish forest responses to disturbances from their undisturbed dynamics (e.g., probability models of disturbance occurrence, classification algorithms, forest health monitoring systems) will obviously need undisturbed records to complement DEFID2 data.

7 | CONCLUSIONS AND OUTLOOK

Evidence is emerging that biotic disturbances have significantly increased in Europe over the last decades (Forzieri et al., 2021; Patacca et al., 2023) and that they will further intensify in frequency and magnitude with global warming (Seidl et al., 2014, 2017). A profoundly changing disturbance regime would play a significant role in the way climate change reshapes European forests (Mauri et al., 2022) and further comprise their stability and sustainability. Despite the environmental and societal importance of this issue, substantial knowledge and methodological gaps in observing, understanding, and predicting biotic disturbances have so far hampered the quantitative assessment of their effects on the biosphere at large scales (Huang et al., 2020). These limitations mostly originate from the lack of large and consistent observational datasets of insect and disease disturbances.

To fill this gap, the Joint Research Centre of the European Commission promoted a joint effort among researchers engaged in mapping forest damages due to insect and disease outbreaks, with the aim to develop an extensive spatially explicit database of such disturbances in European forests. The Database of European Forest Insect & Disease Disturbances (DEFID2) represents the outcome of such an initiative and comprises 676,347 georeferenced records over the 1963–2021 period. The database covers large environmental gradients representative of most European forest types. Furthermore, a satellite-based quantitative assessment of damage metrics, that complements the data collection and harmonization, increases the comparability of data acquired from different methods. We believe that the DEFID2 database can represent a significant benchmark for a multitude of large-scale applications dealing with biotic disturbances. In particular, it offers great promise to improve our understanding of landscape-scale ecological processes underlying biotic forest disturbance, to monitor their evolution in space and time, and to simulate their dynamics in land-climate models.

New online tools developed in the framework of the European Union research scheme, that facilitate reporting damage to trees in forests and cities, can become a powerful way to complement the information collected through existing forest health surveys in various countries. The integration of key plant traits, such as tree age, height, and diameter at breast height, would be particularly relevant to explore host–agent interactions. Citizen science applications such as Silvalert (https://silvalert.net/) aim to raise awareness on forest disturbances, provide real-time information to support management operations. They can also produce information that, after validation, could be included in DEFID2. Ultimately, the usefulness of DEFID2 will depend in large part on its growth to further increase its spatial and temporal extent and representativeness; researchers and institutions interested in contributing to the further development of DEFID2 are therefore warmly invited to reach out to the authors. In particular, disturbance data systematically collected by national forest services would be particularly relevant to populate future DEFID2 releases.

AUTHOR CONTRIBUTIONS

Giovanni Forzieri, Alessandro Cescatti, and Pieter S. A. Beck coordinated the DEFID2 initiative. Bernd Eckhardt led the data collection and harmonization; Agata Elia led the satellite-based characterization. Loïc P. Dutrieux led the implementation of the relational database management system and the R package for data access. Giovanni Caudullo structured the data repository. Andrea Battisti, Constantin Nistor, and Henrik Hartmann provided scientific advice for DEFID2 database design and protocol. Flor Álvarez Taboada, Alessandro Andriolo, Flavius Bălăcenoiu, Ana Bastos, Andrei Buzatu, Fernando Castedo Dorado, Lumír Dobrovolný, Mihai-Leonard Duduman, Ján Ferenčík, Angel Fernandez-Carrillo, Rocío Hernández-Clemente, Alberto Hornero, Săvulescu Ionuț, María J. Lombardero, Samuli Junttila, Petr Lukeš, Leonardo Marianelli, Hugo Mas, Davide Nardi, Marek Mlčoušek, Christo Nikolov, Christo Nikolov, Constantin Nistor, Nicolai Olenici, Per-Ola Olsson, Francesco Paoli, Marius Paraschiv, Zdeněk Patočka, Eduardo Pérez-Laorga, Jose Luis Quero, Marius Rüetschi, Sophie Stroheker collected forest disturbance data. Giovanni Forzieri, Pieter S. A. Beck, Agata Elia, Bernd Eckhardt, and Loïc P. Dutrieux wrote the manuscript with contributions from all co-authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Joint Research Centre Open Data Catalogue at https://data.jrc.ec.europa.eu/dataset/6b2a1a59-5f8a-4bd4-9570-da967f45fd2b.

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