NOTAS DE INVESTIGACIÓN Y RESEÑAS

NEAR-REAL-TIME FORESTS DISTURBANCE MONITORING

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Forests are a key element for carbon sequestration and a major component of rural development, providing habitat for a wide range of species, protective functions for soil, water and infrastructure and contributing goods and services (Ojea, Nunes y Loureiro, 2010). Through a proper management such services are everlasting (Schaich y Milad, 2013). In the last decades, however, climate change, air pollution, fires, insect and pathogens outbreaks, have caused serious threats to forest ecosystems integrity, functions and processes, leading to habitat degradation and the related loss of services (Michel y Seidling, 2014; Senf, Seidl, y Hostert, 2017). Biotic and abiotic disturbances are natural processes driving forest ecosystem dynamics and helping to maintain healthy, heterogeneous forests. However, many forest ecosystems have experienced an increase in disturbances rate, magnitude and frequency, with recent trends reaching an unpre-

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cedented global extent (Weed, Ayres y Hicke, 2013; Millar y Stephenson, 2015). In Europe alone, 17% of forests were affected by some type of disturbance over the past 20 years (Senf y Seidl, 2021). Similar tendencies have been observed over the peninsular Spain where over 100,000 ha of forest are annually affected by fires (Joint Research Center, 2019) while smaller areas are affected by insect outbreaks and pathogens.

The ability to monitor land change at increased frequency is ever more relevant due to the accelerating disturbances affecting forest ecosystems. Indeed, projected changes in global climate due to increasing greenhouse gas concentrations will result in significant effects on terrestrial biomes, particularly forests (Saxe, Cannell, Johnsen, Ryan y Vourlitis, 2001). The rise of temperature and the drop of average annual precipitations in numerous regions of the world have accelerated in the past three decades and are affecting both local and broad-scale ecosystem processes, including disturbance regimes. Indeed, temporal trends observed in forest demography suggest a worldwide increase in tree mortality (Brienen *et al.*, 2015; Senf *et al.*, 2018) with similar trends being observed for the Spanish forests (Astigarraga *et al.*, 2020). Future climate projections predict that disturbances will further intensify (Seidl, Schelhaas, Rammer y Verkerk, 2014) with potentially major impacts on global carbon sequestration (Kurz *et al.*, 2008). Detecting disturbance events, managing emerging outbreaks and predicting where outbreaks will occur requires up-to-date spatially explicit information on the magnitude and extent of disturbance impacts. Therefore, a continuous, accurate monitoring of disturbance type, size, and impact is becoming increasingly important to provide early warning on forest condition. In addition, early detection support salvage logging operations, thereby minimize economic losses (Fahse y Heurich, 2011), or allow for short-term actions aimed at reducing the ecological impact of disturbances.

Developing resilient management strategies requires a robust understanding of forest ecosystem dynamic including disturbance regimes. Understanding the cumulative effects of all disturbance events, occurring in each area and time period, is fundamental to understanding the current state of forest ecosystems, predict future trajectories and develop adequate management plans and policies. Forest condition and disturbance monitoring may rely on information provided by field based statistical networks, by information derived from Earth Observation (EO) data, or by a hybrid approach. Statistic-based systems rely on ground-based networks such as the International Cooperative Programme (ICP-Forests), a systematic transnational network (16 x 16 km grid, 620 plots located in Spain) focused on the appraisal of forest condition. However, the high surveying costs and the lag between in-situ surveying dates makes not only unfeasible but also unattractive forest monitoring activities based exclusively on in situ networks.

Remote sensing-based monitoring requires less effort and time than ground surveys and can be performed at a much higher temporal frequency (weekly or less) with wall-to-wall cover. Therefore, the important information provided by in-situ monitoring networks is increasingly supplemented through remote sensing technologies although ground data are still essential for calibration / validation activities. Changes in forest structure due to fires, insects and pathogens activity, logging and subsequent processes may be identified and monitored by means of remote sensing using optical (Senf *et al.*, 2018; Tanase, de la Riva y Pérez-Cabello, 2011; Hansen *et al.*, 2013), radar (Tanase, Ismail, Lowell, Karyanto y Santoro, 2015, Tanase *et al.*, 2018; Belenguer-Plomer, Tanase, Fernandez-Carrillo y Chuvieco, 2019) or LiDAR (Goetz, Sun, Baccini y Beck, 2010; Montealegre, Lamelas y de la Riva, 2014) sensors. Optic remote sensing is suitable for mapping land-cover since abrupt changes in tree canopy cover can be readily observed. Most algorithms take advantage of wider spectral range (when compared to visual assessments) and the extensive area observed simultaneously to produce wall-to-wall estimates of forest condition. Nevertheless, assessing forest degradation using optic sensors is much more problematic since degraded areas are characterized by changes in forest structure rather than land cover type, i.e., forest canopy cover may not change significantly (Herold y Skutsch, 2011). Similarly, tracking vegetation development is usually limited to the first decade after disturbance (Tanase, de la Riva, Santoro, Pérez-Cabello y Kasischke, 2011). Fewer studies are available for active (i.e., radar and LiDAR) sensors use for forest condition retrieval (Tanase *et al.*, 2018; Solberg *et al.*, 2017; Salberg, Solberg, Weydahl y Astrup, 2009). LiDAR sensors provide very accurate information on forest vertical structure (Nelson, *et al.* 2007). However, spaceborne acquisitions lack continuous spatial coverage and are severely affected by clouds. Conversely, systematic airborne LiDAR data are acquired at rather large intervals over national territories. Since the radar signal is directly influenced by the vegetation structure, Synthetic Aperture Radar (SAR) sensors are more sensitive to temporal changes in forest structure when compared to optical data and less limited by spatial and temporal availability when compared to LiDAR sensors. However, working with SAR data has its own challenges as the signal is affected by forest unrelated factors (e.g., precipitation, topography) which often hinder the retrieval of forest structural information (Tanase *et al.*, 2019). Therefore, an integrated forest monitoring framework is needed to allow for harnessing the strengths of different sensor technologies thus improving the information recovered from each sensor alone.

EO-centric forest monitoring programs need to provide early and adequate information by detecting ephemeral episodes from more permanent impacts across large regions. Early warning is crucial for effective forest disturbance management (Kharuk, Ranson y Im, 2009) with an early-warning system being a key goal for forest management and climate change adaptation (Lange y Solberg, 2008). Such systems need dense temporal series, complete coverage, and algorithms able to take advantage of both, the temporal dimension (Cohen, Yang y Kennedy, 2010) and fusion of diverse sensor technologies. This project tackles such challenges by addressing the entire data-to-information process within an interdisciplinary approach where knowledge from Environmental Science is combined with expertise in Space and Information technologies. To this end, the research aims to develop high added-value content and applications through mass data processing and state-of-the-art modelling implemented on local and cloudbased high-performance computing (HPC) environments for a more effective and efficient conservation of the natural environment.

The project has two specific objectives: 1) appraise spatial-temporal trends in forest disturbance by creating an open access national database spanning the last four decades from historical EO datasets and 2) develop a novel near-real-time integrated forest monitoring framework based on the integration of low-frequency high-resolution (<10m) national airborne data with frequently acquired medium-resolution (10-50 m) spaceborne imagery (Figure 1). The successful completion of these objectives responds to the following questions:

1. What are the main disturbances affecting the Spanish forests? Answering this question will allow identifying the major disturbance agents over the national territory as well as their spatial and temporal distribution over biogeographical regions.
2. Are there significant spatial-temporal trend changes over the past 40 years? What relationships they have with climate, forest type, and management? A detailed picture of the vulnerability of the Spanish forests to global change shall emerge together with die-off spatial-temporal patterns and the existence of hotspot areas.
3. What is the most efficient way to integrate airborne and spaceborne active/passive datasets for forest disturbance monitoring? The most efficient framework that assimilates airborne and spaceborne sensors into an integrated forest disturbance monitoring system shall be provided based on selected large demonstrator areas (LDAs).
4. How forest disturbance and damages should be better communicated and used operationally?

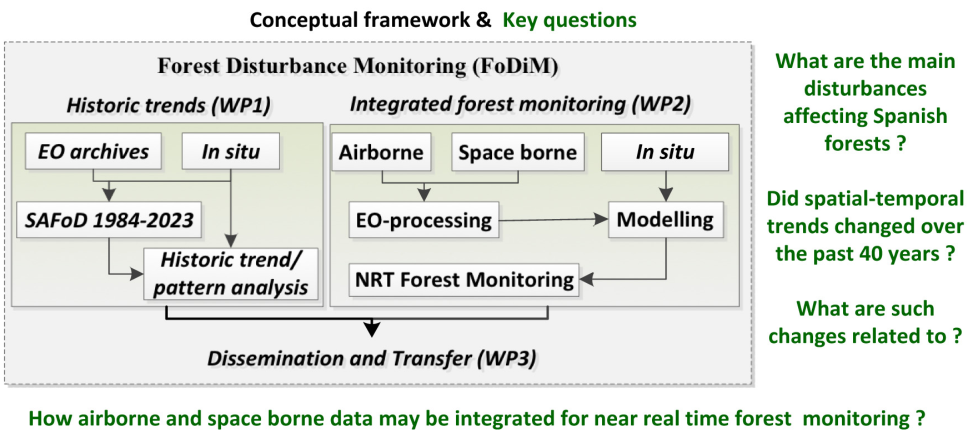

Figure 1. Conceptual framework. SAFoD: Spanish Atlas of Forest Disturbances. NRT: near-real-time.

The project focuses on using a range of airborne and spaceborne sensors and state-of-the-art modelling approaches, calibrated and validated with in situ data from existing monitoring networks. The project has to main objectives: 1) a national-scale historical EO data analysis, and 2) the development of a Near-Real-Time (NRT) integrated forest monitoring system (IFM) system. The first objective shall generate a comprehensive database of forest disturbances (1984-2023), including the main disturbance agents and forest recovery using the historical archive of Landsat 5/7/8 satellites. The database shall be subsequently used to analyze trends and patterns and their potential relationships with changes in climate. The second objective aims at prototyping a framework that assimilates airborne and spaceborne sensors into an IFM developed and implemented over three demonstrator areas (Figure 2). The proposed framework takes advantage of the high accuracy Airborne Laser Scanning (ALS) based forest structure estimates and dense time-series (5-6 days) operational monitoring from Sentinel-1 (S-1) and Sentinel-2 (S-2) satellites. The IFM shall allow for the most accurate information on forest characteristics and condition to be derived and updated every five years using ALS data while also providing near-real-time updates on forest condition and disturbances through the combined used of optical and radar dense time-series. Such time-series shall allow the detection of abrupt deforestation events (fire, logging) as well as more gradual changes of forest condition (i.e., degradation) caused by different agents including drought, insect outbreaks, selective logging, etc. The advantage of an integrated approach is the use of ALS to initialize the algorithm with accurate information on forest status and structure. This initial status will be updated and corrected from subsequent ALS datasets acquired within the National Plan for Aerial Orthophotography (PNOA).

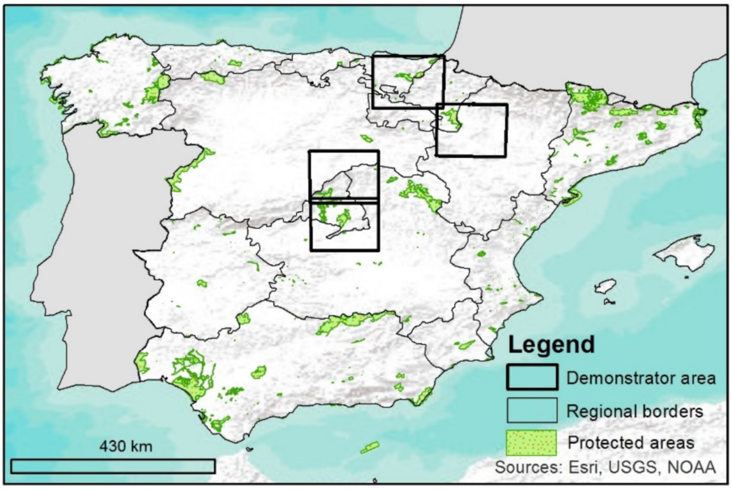

Figure 2. Location of the large demonstrator areas together with the location of the Spanish protected areas.

The project has the capacity to retrieve indicators related to environmental changes by analyzing the time-space dimension of the remote sensing signal from optical, LiDAR, and radar time series. Such an integrated approach provides for deriving spatially explicit information on forest condition and disturbance intensity at regional to national levels over the past 40 years as well as monitor future disturbances within a novel and integrated monitoring system based on active/passive airborne/spaceborne EO datasets. The project will provide wall-to-wall spatially explicit information on environmental changes of the Spanish forests, i.e. the Spanish Atlas of Forest disturbance SAFoD, that will be used to better understand the direction and magnitude of such changes, identify the main drivers underpinning the observed pattern and quantify the vulnerability and resilience of the different forest types across the Iberian Peninsula. Such information is essential to the development of forest policies and management plans that respond to the challenges posed by global change agents. The project will also provide specific approaches and solutions for upscaling local and regional concepts to national conditions providing a framework to assess changes in forest ecosystems status for decades to come. Optical, radar and LiDAR sensors will be integrated and used to develop novel algorithms allowing for a reliable differentiation of real changes in forest cover and structure thus improving existing methods by fusing dense series of radar and optical data with temporally sparser but more accurate LiDAR data.

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