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Review article

# Remote sensing of forest insect disturbances: Current state and future directions

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ABSTRACT

Insect disturbance are important agents of change in forest ecosystems around the globe, yet their spatial and temporal distribution and dynamics are not well understood. Remote sensing has gained much attention in mapping and understanding insect outbreak dynamics. Consequently, we here review the current literature on the remote sensing of insect disturbances. We suggest to group studies into three insect types: bark beetles, broadleaved defoliators, and coniferous defoliators. By so doing, we systematically compare the sensors and methods used for mapping insect disturbances within and across insect types. Results suggest that there are substantial differences between methods used for mapping bark beetles and defoliators, and between methods used for mapping broadleaved and coniferous defoliators. Following from this, we highlight approaches that are particularly suited for each insect type. Finally, we conclude by highlighting future research directions for remote sensing of insect disturbances. In particular, we suggest to: 1) Separate insect disturbances from other agents; 2) Extend the spatial and temporal domain of analysis; 3) Make use of dense time series; 4) Operationalize near-real time monitoring of insect disturbances; 5) Identify insect disturbances in the context of coupled human-natural systems; and 6) Improve reference data for assessing insect disturbances. Since the remote sensing of insect disturbances has gained much interest beyond the remote sensing community recently, the future developments identified here will help integrating remote sensing products into operational forest management. Furthermore, an improved spatiotemporal quantification of insect disturbances will support an inclusion of these processes into regional to global ecosystem models.

## 1. Introduction

Disturbances by insects are natural processes in forest ecosystems and an integral driver of their dynamics, helping to maintain healthy and heterogeneous forests that can provide important ecosystem services (Raffa et al., 2009). However, many forest ecosystems have experienced an increase in the rate, magnitude and frequency of insect disturbances, with recent disturbance activity considerably exceeding levels known from 20th century experience (Millar and Stephenson, 2015). This raised concerns regarding the impact of insect disturbances on biogeochemical cycles (Edburg et al., 2012), especially the carbon cycle (Kurz et al., 2008; Seidl et al., 2014), biodiversity (Beudert et al., 2015; Müller et al., 2008), and the economic value of forests (Dale et al., 2001). Despite the importance of forest insects for tree mortality globally, there is a lack of consistent data sets tracking insect disturbances systematically through space and time (Kautz et al., 2016). This data gap substantially hampers the development of process-based models for making informed prediction of potential future changes under global climate change, and thus the development of adequate management strategies (Kautz et al., 2016; Seidl et al., 2011).

Forest insects can be broadly grouped into xylophagous (e.g. bark beetles) and folivorous insects (e.g. defoliators). There exist also smaller groups of mucivores insects (fluid-feeders), though we do not focus on those here as they are less important in most forest ecosystems. Many bark beetle species of importance in the context of forest disturbance regimes reproduce in the phloem tissue of live and dead trees and – through introduction of associated fungal pathogens – disrupt the translocation of water and nutrients within the tree. A successful infestation of bark beetles can thus be mortal for trees (Raffa and Berryman, 1983). Defoliating insects feed on the needles or leaves of trees, essentially impacting the trees capacity to perform photosynth-

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esis. This can lead to growth reduction, deformation, and – in conjunction with secondary pressures such as simultaneous bark beetle attacks or drought – tree mortality (Cooke et al., 2007). However, after the collapse of defoliator populations trees usually resprout in the following year, or – in the case of some broadleaved tree species – even in the same year.

Insect disturbances act at varying spatial and temporal scales that all need to be considered to develop a holistic understanding of their dynamics, and subsequently predict their future changes (Raffa et al., 2008). While much research has utilized laboratory and field data to understand the drivers of host colonization by insects and their reproductive success, those small-scale drivers are often not sufficient for predicting the landscape- to regional-scale infestation patterns observed in recent outbreaks (Seidl et al., 2015; Senf et al., 2017; Simard et al., 2012). Hence, besides tree- and stand-scale factors, it is also important to understand how insect populations interact with their surrounding landscape, as well as with regional-scale climate. Tackling those larger-scale processes requires data that a) are spatially explicit, b) cover large geographic extents, c) deliver a temporal resolution that fits the life-cycle of the insect of interest, and d) allows for assessing long time series to capture the long-term natural fluctuations that are inherent to insect dynamics. While dendroecology and long-term ecological monitoring allow for an extensive historical view on insect disturbances over relatively large geographic extents (Swetnam and Lynch, 1993), they do not offer the spatially explicit perspective needed for understanding the patterns and interactions of insect outbreaks at the landscape scale. Furthermore, the finest temporal resolution that can be consistently obtained from dendroecological investigations is often only in the range of decades, and an attribution to specific disturbance agents remains challenging (e.g., Janda et al., 2016). Remote sensing largely fulfills all the above-mentioned criteria and serves as a powerful approach to study insect outbreaks across large areas at fine spatial and temporal scale (McDowell et al., 2015; Trumbore et al., 2015).

The biological differences between bark beetles, defoliators of coniferous trees, and defoliators of broadleaved trees explained above suggest that there are specific advantages and disadvantages of applying particular remote sensing methods for mapping their occurrence and infestation severity. However, even though there exist reviews from a regional perspective (Hall et al., 2016), focussing on specific insect types (Rullan-Silva et al., 2013; Wulder et al., 2006a), or general forest health decline (Lausch et al., 2016), we yet lack a systematic, comprehensive, and global assessment of the methods best suited for the remote sensing of varying forest insect agents. A systematic review of the methods applied, and a better understanding of their underlying biological and ecological processes, will help to improve future studies that aim at mapping and estimating insect disturbances. Consequently, we systematically reviewed the approaches employed in the remote sensing of forest insect disturbances, specifically addressing the following three questions:

- What are the insect types, species, and biomes that have been studied using remote sensing?
- What are the methods best suited for mapping disturbances from bark beetles, defoliators of coniferous trees, and defoliators of broadleaved trees?
- What are the challenges for current remote sensing approaches, and how can they be overcome in the future?

We first present a systematic literature review to answer research questions 1 and 2. Subsequently, using a more qualitative approach, we synthesize the results of the systematic review to address research question 3.

## 2. Systematic literature review

### 2.1. Database search

For obtaining an initial sample of the relevant literature we searched the *ISI Web of Science* database (http://www.webofknowledge.com/) with general search terms focussing on the mapping of forest insect disturbances by remote sensing, using the following search string: TS = (bark beetle* OR defoliator* OR insect* OR pest*) AND TS = (forest* OR tree*) AND TS = (remote sensing OR remotely sensed OR mapping OR satellite* OR earth observation*).[1] This initial search led to a total of n = 868 studies. We screened the titles and abstracts of those studies to exclude studies obviously unrelated to our review (e.g., medical studies, studies using remote sensing for guiding field work, simulation studies), which decreased the total number of studies to 149. For those studies, we downloaded the full text for further screening. We subsequently analyzed each study by the following criteria set for the inclusion in our review:

- A specific insect agent must be defined. Studies mapping general forest decline or change due to multiple agents were not considered.
- A map was produced or could easily be produced with the methods described in the paper. Experimental studies limited to a few selected pixels or simulation studies were excluded.
- Studies mapping infestations in plantations or orchards were not considered.
- Approaches must be (semi-) automatic. Studies applying manual digitalisation of remote sensing data or manual mapping from aircrafts (aerial surveys or sketch maps) were not considered.

After applying these criteria, a total of 59 studies were selected for inclusion in the analysis. However, we noted that 16 studies that were initially not included in our sample were frequently cited in other studies considered in our review. After checking them against the above described criteria, we also added those studies to our literature base, yielding a final number of n = 75 studies to be included in the systematic review.

### 2.2. Information extraction and analysis

For each study in the sample, we extracted the same set of attributes for analysis (Table 1). In particular, we noted the insect type (i.e., bark beetle, defoliator coniferous, defoliator broadleaved), the insect species, if the species was native to the ecosystem studied, and its primary host species. Furthermore, we recorded the response variable and how reference data was collected, as well as the location of the study area. To characterize the sensor used in each study, we recorded the sensor name, the spatial, temporal, and spectral properties of the sensor, as well as the sensor. Finally, we noted the classification/regression model used for mapping/estimating infestation, if a fitting technique was applied (for temporal smoothing, etc.), if auxiliary data was used in the model, as well as the measure of accuracy/model performance and the level of accuracy/model performance obtained. For a detailed description of the attributes see Table 1.

After extracting the information for each study included in our analysis, we first mapped and visualized the spatial and temporal distribution of studies and insect types. Moreover, we extracted the biome the study site was located in using the biome classification by Olson et al. (2001). We created statistical summaries of all sensor attributes and methods applied to study insect disturbances, grouped by the four insect types. Finally, we investigated the distributions of accuracies achieved when mapping/estimating disturbances. While

[1] TS = Topic search, including title, abstract, and author keywords. Asterisks (*) are wildcards for any type and number or character.