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Radar Satellite Imagery for Detecting Bark Beetle Outbreaks in Forests

Markus Hollaus [1] · **Mariette Vreugdenhil** [1]

Abstract
Purpose of Review The overall objective of this paper is to review the state of knowledge on the application of radar data for detecting bark beetle attacks in forests. Due to the increased availability of high spatial and temporal resolution radar data (e.g. Sentinel-1 (S1)), the question is how this time series data can support operational forest management with respect to forest insect damage prevention. Furthermore, available radar systems will be listed and their potential for detecting bark beetle attacks will be discussed. To increase the understanding of the potential of radar time series for detecting bark beetle outbreaks, a theoretical background about the interaction of the radar signals with the forest canopy is given. Finally, gaps in the available knowledge are identified and future research questions are formulated which could advance our understanding of using radar data for detecting forest bark beetle attacks.
Recent Findings Few studies already demonstrate the high potential of S1 time series data for forest disturbance mapping in general. It was demonstrated that multi-temporal S1 data provide an excellent data source of describing the phenological characteristics of forests, which provide the basic knowledge for detecting bark beetle induced forest damages. It has been found that the optimal time for data acquisition is April to June for the pre-event and August to October for the post-event acquisitions.
Summary For detecting bark beetle induced forest damages, the literature review shows that mono-temporal radar data are of limited use, that shorter wavelength (e.g. C-band; X-band) have a higher potential than longer wavelength such as L-band and that the current S1 time series data have a high potential for operational applications.

Keywords Forest · SAR · Time series · Damages · Monitoring · Bark beetle

Introduction

Forest disturbances, mainly caused by storm events, ice, snow, fire, and insects, disrupt ecosystem dynamics and significantly influence ecosystem goods and services [1, 2] and strongly impact forest carbon budgets [3••, 4]. Especially, in mountainous regions, the dynamics of forest disturbances are influencing the protective function of forests [5, 6] and, therefore, are an important economic aspect which need to be considered in operational forest management [7, 8]. Due to ongoing climate change and the fact that there is a synchronisation of forest disturbance rates from forest mortality patterns with climate change, the topic of forest disturbance becomes an increasingly important issue. For example, Senf et al. [9] found a relation between satellite-derived estimates of forest disturbance rates and climate-related events since 1985 in forest landscapes of Central Europe. Furthermore, in Seidl et al. [10], an overview is given how climate change may affect disturbance regimes via direct, indirect and interaction effects. They summarized that warmer and drier conditions facilitate fire, drought and insect disturbances, while warmer and wetter conditions increase disturbances from winds and pathogens. Furthermore, in the review paper of Pureswaran et al. [3••], the connection between forest insects and climate change is described. They concluded that the relationships between climate change and forest insects are clear in some species but cannot be generalized to all species. Finally, they concluded that process-based

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✉ Markus Hollaus
Markus.Hollaus@geo.tuwien.ac.at

Mariette Vreugdenhil
Mariette.Vreugdenhil@geo.tuwien.ac.at

[1] Department of Geodesy and Geoinformation, TU Wien, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria

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phenology models permit predictions of population dynamics if input data are appropriate.

Apart from climate-disturbance relationships, contemporary frequent and severe abiotic and biotic damage incidents similarly affecting primary and managed conifer forests are due to increasingly high disturbance susceptibility with regard to stand history, development stage and structure [11, 12]. Species composition, stand age and density in combination with increased temperature and drought conditions were identified as the most relevant parameters for explaining/predicting salvage cuttings in Austrian Norway spruce forests following attacks of Europe's most important forest insect pest, the Eurasian spruce bark beetle, *Ips typographus,* during the period 2014–2016 [13]. Documentation of forest damage [14] shows that for example in Austria a strong increase of bark beetle induced timber is recorded since 1990 and reaches approximately 20% and 28% of the total harvested timber for 2017 and 2018, respectively. Similar situations are observed for other European and North American countries [15].

Based on the increased frequency of forest insect attacks and the attendant increase of ecological and economic impacts, there is a strong demand for remote sensing–based monitoring approaches. Several publications can be found that use different remote sensing data for detecting forest insect attacks. Most studies use optical remote sensing data, and only few studies use radar data. Optical remote sensing makes use of the large absorption of light in the visible spectrum and reflection in the near infrared and short wave infrared spectrum during photosynthesis to derive information about the forest canopy. Radar systems transmit pulses of electromagnetic energy and record the reflected signal at the sensor from the area of interest. Most systems, which aim at monitoring the Earth's surface, operate in the microwave domain, with frequencies between 3 and 30 GHz. In the microwave domain, the backscattered signal is sensitive to a number of land surface parameters, including, but not limited to, water content in soil and vegetation and vegetation structure. However, most of the investigated publications use optical satellite data as has been summarized in the recent review paper about remote sensing of forest insect disturbance mapping from Senf et al. [16], which gives an extensive overview of different insect types and remote sensing data and methods for mapping disturbances. In this review paper, only one paper was mentioned that uses TerraSAR-X radar data in combination with optical high-resolution RapidEye data for the early detection of bark beetle green attacks [17]. Furthermore, the review paper of Stone and Mohammed [18] gives an overview of applications of remote sensing technologies for assessing planted forests damaged by insect pests and fungal pathogens. They conclude that the simultaneous acquisition of spectral and 3D point data will have the highest benefit for assessing tree health in a cost-effective manner. From an operational point of view, the spectral properties of optical satellite data have the benefit that several spectral bands provide the potential for mapping forest disturbances as summarized in the above cited review papers. The majority of the applied algorithms for forest disturbance mapping is based on the monitoring of forest dynamics and thus a high temporal resolution is essential. However, for optical satellite data, this requirement can limit the application for up-to-date monitoring due to the sensitivity of optical remote sensing to clouds, aerosols and smoke. The advantage of radar is that it is not hindered by cloud cover, smoke, aerosol contamination and low solar illumination. Due to the longer wavelength of microwaves compared to optical remote sensing, the penetration depth in vegetation is larger, making it sensitive to the canopy and woody parts of the vegetation [19].

Nonetheless, until recently, the temporal and spatial resolutions of publicly available radar data were not sufficient for detecting forest insect attacks. With the launch of ESA's Sentinel-1 satellite constellation carrying C-band synthetic aperture radar instruments, cross- and co-polarized backscatter data are now available for the first time at the spatial and temporal resolution needed. Hence, the overall objective of this paper—to review the state of knowledge on the application of radar data for detecting bark beetle attacks in forests—is formulated. Based on a systematic literature review of papers published since 2000, different applications of radar data for detecting forest disturbances due to bark beetle attacks including their applied methods are summarized. Additionally, an overview of available types of forest insect infestations and the related physiological changes in the canopy with respect to remotely sensed properties is given. This review paper focuses on bark beetle induced forest damages as these insect attacks lead to extensive calamities in coniferous forests. As the interaction of the radar signal with forest canopies is different from the spectral properties that are important in optical remote sensing, an introduction to radar and microwave remote sensing is given, including a theoretical background about the interaction of microwaves with vegetation. Finally, gaps in the available knowledge are identified and future research questions are formulated which could advance our understanding of using radar data for detecting forest bark beetle attacks in an operational sense.

Types of Bark Beetle Infestations and Impact on the Canopy Properties for Optical and Radar Data

The most important forest insects can be grouped into *xylophagous* and *folivorous* insects. As summarized in Seidl et al. [10], bark beetle species are the most prominent *xylophagous* insects, whereas defoliators are the most important species in the group of *folivorous* insects. The insects of these two groups affect trees in a different manner. Bark beetle species bore into the phloem of trees, copulate, mine galleries and oviposit [20]. Furthermore, they introduce several species of fungi that colonize the phloem and vascular tissue. Finally, the translation of water and nutrients within the tree is getting interrupted leading to the death of the tree. In contrast to bark beetles, defoliating species feed on leaves and needles and thus influence the photosynthetic activity of a tree. This can lead to growth reduction, deformation or to tree mortality. Depending on the infestation intensity and the consequent degree of defoliation and the surrounding environmental stress factors (e.g. drought), trees can regenerate in the following year or in the case of some broadleaved tree species even in the same year [10].

For mapping infestations with remote sensing techniques, knowledge about the physiological effects of the attacks in the forest canopy is essential. Niemann and Visintini [21•] describe three stages that occur during a bark beetle attack. The green attack stage occurs during the host colonization and the development of the first bark beetle population. During this phase, the physiology of the tree is not influenced and no visual change in the canopy can be observed, even though the tree is getting stressed due to the increased production of resin and due to decreased water availability. The detection of this very early infestation stage would have the highest benefit for supporting operational forest management, but remote sensing has been of limited success until now [21•]. A reliable detection of infested trees can only be done with ground surveys by searching for entry and exit holes on the bole, boring dust and pitch tubes, which are all indicators of beetle infestations [22]. However, such field work can only be done for sample plots due to the high demand of time and consequently costs for such in situ measurements.

The red attack stage includes the period where the colour of needles turns to yellow and brown and where the tree starts to lose needles. Additional to the changing colour of the canopy, the needle water content is the most important physiological change during the red attack stage [23, 24]. The final grey attack stage describes the period where the tree will lose all of its foliage. From a remote sensing perspective, short-wave infrared wavelengths are most sensitive to changes in the needle water content [10]. The majority of the studies investigated in the review of Seidl el al. [10] used the normalized difference vegetation index (NDVI) for mapping broadleaved defoliations while different indices were used for mapping coniferous defoliation (NDVI, Normalized Burn Ratio, Moisture Stress Index, Leave Area Index). For mapping bark beetle infestations, the most frequently used index was the difference in the Tasseled Cap Wetness component. However, when doing time series analyses based on spectral images for detecting bark beetle infestations, one has to consider that there is a natural decrease in the chlorophyll content of needles during fall and winter seasons. This decline in chlorophyll content is due to dormancy and frost hardening of the needles which is required in order to protect foliage against photo-oxidative damages [25].

Characteristics of Radar Backscatter from Forests

Radar systems transmit and receive pulses of electromagnetic energy. For most radar systems, two polarizations are common, vertical polarization (V) which is perpendicular to the surface and horizontal polarization (H) which is parallel to the surface. The amount of electromagnetic energy intercepted and re-radiated is a complex combination of multiple factors including electromagnetic and geometric properties of the target and sensor specifics such as wavelength and polarization of the transmitted and received signal. The energy intercepted and reflected is described by the so-called radar cross section. In remote sensing of the Earth's surface, the target is an area in which it is assumed that no single scatterer dominates. To compare measurements from different sensors with different footprints, i.e. target areas, the radar cross section can be normalized by the area, resulting in the backscatter coefficient.

The most important electromagnetic properties of the media for microwave remote sensing are the electric permittivity. It is a complex number with a real and imaginary part, where the real part is often referred to as the dielectric constant. The dielectric constant (ε) of the medium with which the wave interacts plays an important role in the amount of backscattered energy. In the microwave domain, electromagnetic waves incident on the Earth's surface excite water molecules. The dipole character of water causes the water molecules to continuously reorient in the electromagnetic radiation's oscillating electric field. This leads to high ε values of water ($\varepsilon = 80$), compared to dry vegetation matter and soil ($1.5 < \varepsilon < 2$) [25, 26].

The geometric properties of the target area influence the type of scattering. If a medium is homogenous, most of the electromagnetic wave is scattered at the boundary of the surface. The amount of energy reflected can be described by the Fresnel coefficient which is a function of incidence angle and ε. This mechanism is called surface scattering or specular reflection. Volume scattering occurs if a medium is inhomogeneous and the signal penetrates the lower medium. Within the medium, randomly distributed dielectric inhomogeneities scatter the incoming electromagnetic waves in all directions regardless of incident angle [26]. The amount of energy returned to the sensor is proportional to the number of dielectric inhomogeneities and the difference in ε between them and the medium.

The total backscatter of a vegetated surface can be described by scattering from the soil, the vegetation and an interaction between the two. Soil and vegetation produce two different scattering mechanisms, namely surface scattering and volume scattering. Vegetation is often described as a cloud of water droplets held in place by dry matter: an inhomogeneous medium with randomly distributed dielectric inhomogeneities. Since vegetation consists for a large part of water, ε of the total vegetation increases rapidly with increasing above ground biomass and moisture status. From this, it can be inferred that backscatter increases with increasing above ground biomass and moisture status.

The dielectric inhomogeneities can also change the polarization of the incident wave. Although this does not happen to a large degree, a change in polarization is more likely to occur with volume scattering or with interaction between the soil and the vegetation. Because of the low occurrence, cross-polarized backscatter (HV or VH transmit-receive) is usually lower than co-polarized backscatter (HH or VV transmit-receive). It does, however, show a stronger increase with volume and double-bounce scattering than co-polarized backscatter. Thus, when describing vegetation as a water cloud, it can be inferred that cross-polarized backscatter is more sensitive to changes in vegetation.

In order to use radar data for forest monitoring, it needs to be taken into account that, depending on the density of the vegetation canopy, wavelength of the signal and the incidence angle of the observations, microwaves penetrate the vegetation and scattering from the soil or from soil-vegetation interaction could contribute to the total backscatter signal [27]. Most studies agree that the contribution of the soil and soil-vegetation interaction is small in co-polarized backscatter from forests, but not negligible. Especially for longer wavelengths, low biomass forests, high soil moisture conditions or for lower incidence angles the total backscatter signal is sensitive to the soil surface [28–31]. In addition, due to its sensitivity to volume scattering, studies have found cross-polarized backscatter to be most sensitive to changes in forest above ground biomass and that the contribution of soil and soil-vegetation interaction was found to be negligible [31–33].

Apart from the above ground biomass and moisture content, the structure of the vegetation can play a large role on the temporal backscatter signal. This is especially the case in deciduous forests where major changes in structure occur due to the development of the foliage. One of the first studies addressing the effect of structural changes of vegetation on the backscatter signal was performed by [27] when defoliating corn. The effect of each major plant constituent, i.e. leaves, stalks and fruits, on backscatter at 5.1 GHz was investigated. For high incidence angles, backscatter was higher from defoliated corn, i.e. stalks and cobs, than from the whole plant. The backscatter from stalks or interaction between soil and stalks is very significant but is strongly attenuated by the presence of leaves. In deciduous forests, similar behaviour was observed where higher backscatter was often found in winter followed by a drop in backscatter in spring and summer and an increase in autumn. This was attributed to the change in scattering mechanism from volume to surface scattering and the contribution of soil and soil-vegetation scattering to the total signal when no foliage is present [28, 34•, 35, 36, 37•]. For coniferous forests, this temporal signature was not observed, and low backscatter was observed in winter and high backscatter in summer [34•, 35, 37•]. A recent study on backscatter from Sentinel-1 over a deciduous forest in France showed that the ratio of co- and cross-polarized backscatter coincides temporally with NDVI, increasing in spring and decreasing in autumn. However, no conclusions were given to what drives the variations in the so-called cross ratio [35]. The potential of radar for monitoring changes in forest structure and moisture content was also demonstrated by studies of drought effects in the Amazon. Saatchi et al. [38] showed the complementary information which can be gained next to optical observations when investigating the effects of the Amazonian drought of 2005. A decrease in backscatter was observed after the 2005 drought, which took place over a long time period, and was attributed to a reduction in canopy water and a change in structure.

Radar Data for Bark Beetle Disturbance Mapping

This review paper was based on a screen of the literature between 2000 and 2019 using the ISI Web of Science database (http://www.webofknowledge.com/) and Scopus (https://www.scopus.com) with the general search terms focussing on synthetic aperture radar, forests and insect disturbances. In detail, the following search string was used: ALL FIELDS: (sar OR radar OR microwave OR sentinel*1 OR ers* OR tandem-x* OR l-band) AND ALL FIELDS: (disturbance OR insect OR attack OR beetle) AND ALL FIELDS: (satellite OR airborne) AND ALL FIELDS: (forest OR tree). Within the time period from 2000 to 2019, 105 hits appear containing these keywords in all fields. After a screening of the results, only four publications could be identified as being relevant. In the following paragraphs, an overview of these publications is given.

Ranson et al. [39] explored the use of combined use of mono-temporal JERS and Radarsat data for detecting insect damages in Siberian forests. They used co-polarized (HH) JERS and Radarsat data from 2 years. After the pre-processing steps, they applied a 3×3 Frost filter to each SAR data set to reduce the speckle. For both data sets, the backscatter coefficients and the standard deviations showed low differences across insect damaged and healthy coniferous forests. As a reason for that, they argued that for JERS the damaged foliage have a negligible influence on the backscatter signal because they are too small. For Radarsat, only the separability between coniferous forest and clear-cuts was high. The reason for this can be found in the occurring volume scattering within the tree canopies, whereas volume scattering from grassy clear-cuts is small. The combined use of Radarsat and JERS slightly increased the classification accuracies and 29% of the severely insect damaged classes and 46% of the moderately insect damaged area could be classified. Finally, they concluded that the results were limited when using any single-channel radar data.

Kaasalainen et al. [40] studied the potential of ERS-2 SAR data for detecting defoliation of Scots pine dominated forest located in eastern Finland caused by the European pine sawfly. They used terrestrial laser scanner (TLS) to examine the defoliation during the active period of the pine sawfly hazard. The first measurement was undertaken during the early phase of defoliation and the second following the defoliation period. For the study area, seven ERS-2 images were available from the same orbit and cover the time period from before and after the defoliation. For all images, only the amplitude information of backscattering signal was available. For their analyses, the ERS-2 backscatter values were averaged using a circle with a 50-m radius to reduce speckle. The results show only a slight change in the averaged SAR backscatter for those plots where defoliation could be observed in the TLS data. For plots where signs of defoliation were not present, little or no changes in the backscatter were observed. As no weather data was available for the acquisition times, the influence of the soil surface and vegetation moisture to the backscatter signal could not be investigated in this study.

Ortiz et al. [17] evaluated the capabilities of RapidEye and TerraSAR-X imagery for detecting areas affected by bark beetle green attacks. They investigated generalized linear models, maximum entropy and random forest for detecting bark beetle infested areas in a flat study area in south-west Germany. The RapidEye and the TerraSAR-X data were acquired in two consecutive days at the end of May. Both data sets were orthorectified using a high-resolution digital surface model with a resolution of 2 m derived from airborne laser scanning data. To investigate the potential of both data sets for bark beetle green attack detection, explanatory variables were derived from circular plots with a radius of 5 m covering either only attacked or vital trees. The explanatory variables from TerraSAR-X were the standard deviation, max, min, mean, median and the first and third quartiles of the backscatter distribution. The analyses have shown that the third quartiles and the median of the backscatter were higher for attacked plots than for vital plots. They achieved an overall accuracy of 87% (kappa 0.23) for the TerraSAR-X data and 94% (kappa 0.51) for the RapidEye data. Finally, they conclude that improvements could be expected if multi-temporal SAR data and/or varying polarizations are available.

Tanase et al. [41] used ALOS L-band spaceborne synthetic aperture radar (SAR) within a change detection framework to delineate forested areas affected by wind and insect disturbances. Several SAR images from the same orbit before and after the bark beetle attack were selected as a basis for a pixel-based comparison. The cross-polarized (HV) channel was mainly investigated because of its sensitivity to forest structural characteristics and their change. The backscatter coefficient was normalized with a DTM, and a multi-temporal filtering was applied to decrease speckle. The multi-temporal filtering was based on five pre-event and six post-event SAR data sets. Radar change ratios were computed using pre- and post-disturbance averaged backscatter coefficients to better represent the forest condition by removing the stochastic part of the signal. They found out that a change of the backscatter coefficient of − 1.0 dB is a consistent indicator of forest structural changes induced by bark beetle attacks. They also discuss the influence of weather conditions to the discrimination capacity. For example, the drier conditions of the reference data set and/or wetter conditions for the remaining images lead to nearly no changes of the backscatter coefficients. The classification of the areas affected by bark beetle outbreaks was done using a threshold approach and support vector machines based on the backscatter change ratios. They reached overall accuracies ranging from 74 to 91% depending on the selected image pair. They conclude that the classification accuracy for windthrow affected areas was high and lower for bark beetle–induced damages due to the fact that changes are more abrupt for windthrow than for insect outbreaks. They also state that the interpretation of the backscatter signal can be complex because of the multitude of factors affecting them, the limitations due to the density of the radar observations and that it is difficult to extract the specific stress factor.

In a more general sense, few studies are available that use SAR data for detecting forest disturbances. Even though these studies are not focussing on bark beetle disturbance mapping, their applied methods could be useable for it. For example, De Grandi [42•] used spatial wavelet statistics of ENVISAT ASAR and ALOS PALSAR backscatter to describe the structure of degraded forests in Cameroon, Central Africa. They found out that analytic parameters describing the functional form (i.e. third-degree polynomial function) of the scaling signatures show statistically significant differences between the signatures of intact and degraded forests for ENVISAR ASAR data. For the ALOS PALSAR, no significant differences could be found. As a reason for that the authors argue that L-band penetrates more into the canopy, and therefore, the observed backscatter texture is influenced more by the distribution of large scattering elements and by the ground return, whereas the shorter wavelength of the C-band ENVISAT ASAR is able to describe the canopy much better. Lei et al. [43] used spaceborne repeat-pass InSAR correlation measurements in combination with a physical InSAR scattering model to detect forest disturbances over selective logging sites in Queensland, Australia. They used dual-pol ALOS PALSAR InSAR coherence data with a temporal baseline of 92 days. The basic idea of their approach is to compensate for the scene-wide mean behaviour of the volumetric and temporal decorrelation effects and then use the residual decorrelation as an indicator of forest disturbance. The detected forest disturbance areas (i.e. forest and non-forest areas) were compared to results from Landsat time series with a relative RMSE of 13% over 0.81 ha forest stands. One limitation of this approach is that the disturbance affected area cannot be large compared with the spaceborne InSAR image itself because the mean behaviour of the volumetric and temporal decorrelation effect is estimated from the scene-wide forest coherence distribution.

Discussion and Outlook

The reviewed papers show the limits of mono-temporal radar images for forest disturbance mapping. Since the availability of Sentinel-1 data, the popularity of radar images for forest disturbance mapping has increased. In addition to the freely available Sentinel-1 data, other radar sensors exist but often their data are not freely available, especially radar data with X-band are often not freely available. An overview of available and planned satellite radar sensor is given in Table 1. An extensive overview of satellite missions can be found in the eoPortal Directory [44].

For Europe, the Sentinel-1 satellites offer high temporal (3–6 days) and spatial (5 × 20 m) resolution, which are independent of the cloud clover. Time series from Sentinel-1 are promising not only for bark beetle disturbance mapping but also for other forest disturbance mapping applications such as windthrow or clear-cut detection. For example Rüetschi et al. [45] used Sentinel-1 C-band VV and VH polarisation data for a rapid windthrow detection in mixed temperate forests in Switzerland and northern Germany. They used five Sentinel-1 acquisitions before the event and ten after the storm event including ascending and descending data. The backscatter values of Sentinel-1 were normalised using the modelled local illuminated area based on a DTM rather than a modelled local incident angle based on an ellipsoid. In this way, the influence of the topography on the SAR acquisition is mitigated and the modelled illuminated area was exported as an additional input layer for the further forest disturbance mapping. For the detection of disturbed forest areas, the change detection method "image differencing" was applied for VV and VH polarisations. The mean and the standard deviation were calculated for the difference images. By summing up the differences of VV and VH polarised backscatter values, a heuristic windthrow index was calculated, which was the basis for a decision tree classification. The results show that the backscatter from windthrown areas was typically about 0.5 dB higher than before the storm event. The detected windthrown areas had a minimum extend of 0.5 ha and a producer accuracy of 0.88 and a user accuracy of 0.85. Also, Hirschmugl et al. [46] showed the potential of Sentinel-1 time series data in combination with optical Sentinel-2 and Landsat-8 data for forest disturbance mapping in tropical forests where cloud cover is commonly the limiting factor for using optical data only. The Sentinel-1 data consists of ten acquisitions with single polarisation (VV) from the same orbit acquired within 9 months. In a first step, the forest disturbance mapping was done in parallel for the radar and the optical data. For the combination of both results, the Bayes' theorem was used. The results showed the highest detection accuracies for the combined approach (83.7% for the area-based and 97.1% for the plot-based validation). Furthermore, the results showed for plot areas < 1 ha lower detection accuracies for radar data than for optical data.

Furthermore, Sentinel-1 time series were used for distinguishing forest from non-forest areas or for tree species classifications. For example Dostálová et al. [47] used Sentinel-1 time series data for forest area delineation with a spatial resolution of 10 m in the eastern part of Austria and achieved accuracies of 88% compared to a forest mask derived from airborne laser scanning data. A similar result can also be found in the study of Dostálová et al. [34•], in which dense Sentinel-1 time series backscatter signals were used for forest area delineation and classification into tree species groups. For three European study sites, they achieved overall accuracies of 86–91% for the forest area delineation and 65–85% for the classification into broadleaf forests, coniferous forests and non-forest classes. A similar result is also reported in Rüetschi et al. [37•]. They achieved an overall accuracy of 86% for the classification into coniferous and deciduous forests and 72% for the classification of three different tree species. These studies used the differences in the backscatter seasonality between different tree species. Backscatter variations were further found to hint at differences in the forest structure (mainly tree heights) and vegetation cover; however, differences were less pronounced than between forest types [47].

Also, Rauste et al. [48] used Sentinel-1 time series data over a period of 1 year to describe the temporal behaviour of the C-band backscatter for areas representing areas clear-cut during the Sentinel-1 acquisition period, unchanged forest areas and areas clear-cut before the Sentinel-1 acquisition started. The analyses were done for a boreal forest site in Finland. They could not only show the potential for detecting logged forest areas despite high sensitivity to seasonal and weather conditions but also mention that the detection of logging areas was only successful for good scenes. Consequently, they suggest the use of Sentinel-1 data from two winters for the clear-cut mapping.

In addition to these summarized studies, Hollaus et al. [49••] analysed the potential of Sentinel-1 time series data for recognizing the beginning of bark beetle infestations. Within their study, homogenous areas with vital and infested forest stands were analysed separately for a study area in the north-eastern part of Austria. These forest

Table 1 Overview of operating and planned radar sensors

Sensor	Launch date	Band	Spatial resolution (m)	Orbital repeat (days)	Polarisation	Owner/operator	Scientific data access
ALOS-2 PalSAR	2014	L	10–100	14	Fully polarimetric	Japan Aerospace Exploration Agency	freely available
NISAR	Scheduled 2021	L	3–10	12	Fully polarimetric	NASA	?
RADARSAT-2	2007	C	3–100	24	Fully polarimetric	Canadian Space agency (CSA)	Restricted
Sentinel-1	2013	C	10	12	VV, VH (over land)	European Space Agency	freely available
RADARSAT-constellation (3-satellites)	Scheduled 2019	C	1–100	12	Fully polarimetric	Canadian Space Agency	?
Risat-1	2013	C	1–50	25	Fully polarimetric	Indian Space Research Organisation	Available to Copernicus users
PAZ/PAZ 2 SAR	2001/2018	X	0.25–40	> 2	Fully polarimetric	Spanish Space Agency	Restricted
TerraSAR-X	2007	X	1–16	11	Fully polarimetric	German Aerospace Centre (DLR)	Restricted
Tandem-X	2010	X	1–16	11	Fully polarimetric	German Aerospace Centre	Restricted
Cosmos Skymed-1/2	2007/2010	X	1–100	16; revisit time for the full constellation is in the range of few hours	Fully polarimetric	Italian Space Agency	Restricted
TecSAR	2008	X	1–8	14	Fully polarimetric	Israel Aerospace Industries	Restricted
Kompsat-5	2013	X	1–20	28	Fully polarimetric	Korean Space Agency	Restricted
Kompsat-6	Scheduled 2020	X	0.5–20	11	Fully polarimetric	Korean Space Agency	?

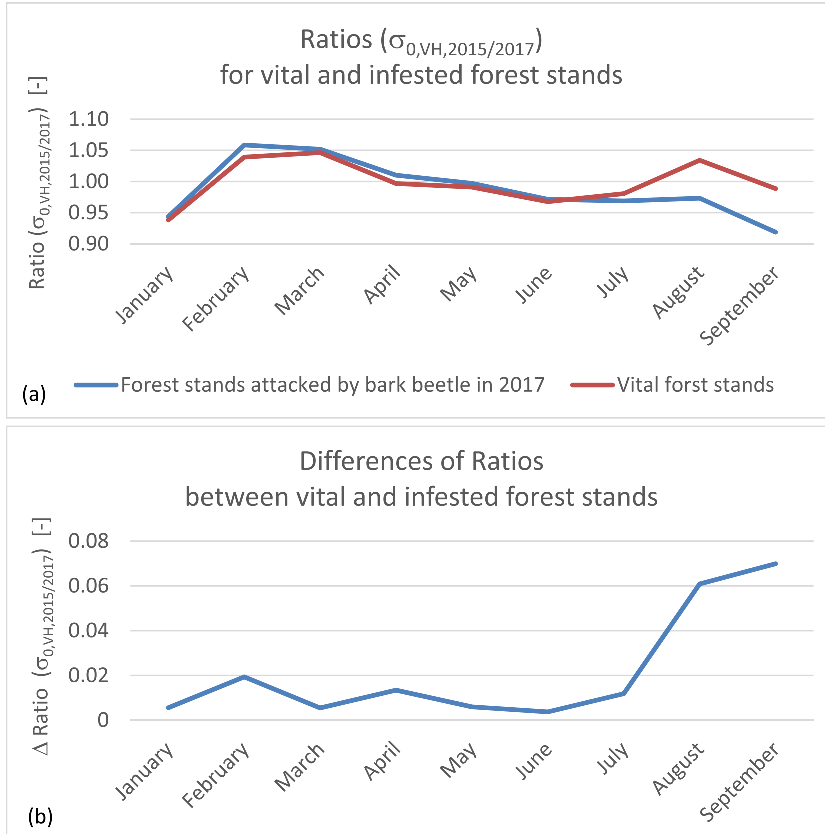

Fig. 1 Monthly averaged Sentinel-1 backscatter ratios for bark beetle infested and vital forest patches. **a** The ratios of the monthly averaged backscatter values for vital and infested forest stands. **b** The differences of the ratio values

stands were derived from Sentinel-2 time series by applying a change detection approach. As the backscatter signal underlies a natural variation due to phenological changes of the canopy and the moisture condition in the canopy and the terrain [34•] monthly ratios were calculated for vital and infested forest stands from backscatter coefficients from the year before the attack and the year of the bark beetle attack. In Fig. 1a, the ratios of the backscatter coefficients for vital and infested forest stands are given, whereas in Fig. 1b, the difference of the ratios is shown for the VH polarized backscatter values.

For this analysis, Sentinel-1 data from the year 2015, where for this investigation area no bark beetle attacks took place, and Sentinel-1 data from the year 2017, where several bark beetle attacks occur, were selected. The Sentinel-1 time series analyses showed a clear difference of the backscatter coefficients between vital and infested forest stands of ~1 dB for both VV- and VH-polarized Sentinel-1 backscatter values. The differences can also be seen in the ratio values as shown in Fig. 1 and start approximately in July to August, which corresponds well with a terminated development of the first filial generation and starting of tree dieback, corresponding to the grey stage. However, crowns of Norway spruce often remain green long after a bark beetle attack was initiated, and stand mortality may be detected only months later. Due to missing reference data with detailed information about the degree of infestation, it could not be analysed which degree of bark beetle related damage can be recognized in Sentinel-1 time series data. In addition to the used differences in the backscatter values for vital and infested forests, one has to consider annual differences in the backscatter values. For example Rüetschi et al. [37•] showed inter-annual differences of the backscatter from coniferous study areas. The seasonal variations are minimized by calculating the ratios between the backscatter signals. However, the influence of the moisture conditions in the canopy as well as in the terrain surface was not considered in this study yet. The consideration of local variations in the backscatter behaviour could improve the detection accuracy by applying local adaptive thresholds in the change detection workflow.

Conclusions

The conclusion gives a short summary of the main findings of the reviewed publications for forest disturbance mapping with the focus on insect induced damages. The potential and the limitations for operational applications are summarized, and future research questions are formulated.

The following conclusions are drawn:

1. Defoliators and bark- and wood-boring insects have the most potential to cause damage in forests. The most prominent insects are bark beetles and after an attack trees commonly die within few months. In Niemann and Visintini [21•], three stages are defined that occur during a bark beetle attack, the green, the red and the grey attack stage. From a remote sensing perspective, the detection of the green attack stage has had limited success as only slight changes are ongoing in the foliage during this stage.
2. Until the start of the Copernicus Sentinel-1 satellites, very few radar data sets were used for detecting forest disturbances due to insect infestations. The available sensors (i.e. JERS, ERS-1, Radarsat, TerraSAR-X, ALOS PALSAR) operate in different wavelengths (X-, C-, L-band) and have either limited spatial or temporal resolution. Most of the studies used the backscatter signal from acquisitions from the same orbit (either ascending or descending), and only in the study of Lei et al. [43], ALOS PALSAR InSAR coherence data were used.
3. Concerning the processing steps and the applied methods for disturbance mapping, it can be concluded that after topographic correction, speckle reduction is undertaken by applying various filters or by averaging the backscatter signal for plots or forest stands.
4. Several studies have shown that shorter wavelengths (e.g. C-band; X-band) have a higher potential than longer wavelengths, such as L-band radar data, for detecting insect induced forest damages. For example De Grandi [42•] argued that L-band penetrates more into the canopy, and therefore, the observed backscatter texture is influenced more by the distribution of large scattering elements and by the ground return, whereas the shorter wavelengths of, e.g. the C-band are able to describe the canopy much better.
5. The high temporal and spatial resolutions of Sentinel-1 time series have shown a high potential for forest disturbance mapping. Until now, the Sentinel-1 data have been mainly used for windthrow mapping (e.g. [45]). Based on deviations from the natural variability of the backscatter signal during the phenological cycle ,Hollaus et al. [49••] demonstrated for the first time the potential of this data source for detecting bark beetle infestations in coniferous forest.
6. Although though there is still a lack of knowledge about the applicability of Sentinel-1 time series for insect disturbance mapping, the study of Hollaus et al. [49••] suggested that the optimal time for data acquisition is April to June for the pre-event and August to October for the post-event acquisitions.

The following open research questions are formulated:

1. Commonly speckle reduction is done by applying filters with a fixed kernel size and shape. As insect-induced forest damage starts within small forest patches that are covered by only a few radar pixels, this type of speckle reduction leads to an averaging and consequently to “mixed” pixels. Therefore, research is needed around how a land cover–dependent and/or time-dependent speckle reduction can improve the detectability of forest disturbances.
2. The reviewed studies have shown that the low temporal resolution is the most limiting factor in using radar data for the detection of insect induced forest damages. The new Sentinel-1 time series data allows the description of phenological characteristics with a high level of detail, which is the basis for forest disturbance mapping. As shown in the studies of Dostalova et al. [34•] and Rüetschi et al. [37•], the backscatter signal has an annual but also inter-annual variability. Furthermore, local variations can occur. Therefore, research is needed around how these small scale variations (i.e. in time and space) in the backscatter signal can be considered. This research also needs to consider influences from varying satellite orbits, i.e. ascending and descending.
3. From an operational forest management point of view, it is important to know the degree of damage (i.e. green, red, grey attack) or the minimum mapping unit that can be derived from radar data. To answer this research question, appropriate reference data are necessary.
4. In the reviewed papers, only one [43] used coherence data. Due to the relatively long temporal baseline of 92 days and the fact that they used L-band data, the results for detecting insect infested forest areas were not satisfactory. Due to the availability of C-band, Sentinel-1 data research is needed to analyse the potential of the coherence information for forest disturbance mapping applications.
5. As already shown in several studies [37•, 50, 51], Sentinel-1 time series data in combination with optical data from, e.g. Sentinel-2, have a high potential for forestry applications. For insect-induced forest disturbance, mapping further research is needed to explore the full potential of multi-sensor data.

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Compliance with Ethical Standards

Conflict of Interest Markus Hollaus and Mariette Vreugdenhil declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- • Of importance
- •• Of major importance

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