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Canopy chlorophyll content retrieved from time series remote sensing data as a proxy for detecting bark beetle infestation

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ABSTRACT

The European spruce bark beetle (*Ips typographus, L.*) is an invasive species resulting in a high degree of fragmentation, forest productivity, and phenology. Understanding its biology and its early detection based on its behaviour is essential for its successful management and eradication. This study demonstrates the potential of the canopy chlorophyll content (CCC) product retrieved from remote sensing datasets to detect early bark beetle infestations in the Bavarian Forest National Park. Time series CCC maps were generated through radiative transfer model inversion of images from RapidEye and Sentinel-2 (2011–2018). The CCC products were then classified into stressed and healthy classes using calculated CCC mean and variance values obtained for infected and healthy Norway spruce trees in 2016. The location of infected plots obtained from the interoperation of resolution (0.1 m) aerial photographs was used as reference data to validate the accuracy of the infestation maps generated from CCC. Validation of the infestation maps indicated a classification accuracy of up to 78%. Our results demonstrated that CCC products derived from satellite remote sensing data were a rigorous proxy for early detection of bark beetle infestation. Hence, CCC products may play a significant role in understanding the dynamics of the Infestation and improving the management of bark beetle outbreaks in forest ecosystems. Inclusion of other remotely sensed plant traits as additional parameters in the model, such as dry matter and nitrogen, may further improve the accuracy of early detection of bark beetle infestation using satellite remote sensing.

1. Introduction

The spruce bark beetle (*Ips typographus, L.*) is considered the most critical disturbance agent in European forest ecosystems (Ohrn et al., 2014). Disturbances induced by bark beetle have increased over the past decades in temperate and boreal forests, and a further increase in disturbance frequency and severity is expected due to global climate change (Bentz et al., 2010). The swarming of bark beetles usually starts mid-April when the air temperature reaches the threshold of 16.5 °C (Ohrn et al., 2014; Wermelinger, 2004). After being infested forest stands (trees) exhibit three distinct stages: green, red, and grey attack (Wermelinger, 2004). During the early stage (green attack), the foliage is still alive and visually green. In this stage, the newly hatched generation of beetles is developing within the inner bark of the infested trees. The infested tree will stay green until late July, when the foliage colour changes (to red) become apparent. At the red attack stage, the bark beetles have already left their host trees and started to attack new trees (Abdullah et al., 2018). While at the grey attack stage, the tree is dead and totally defoliated.

Management interventions should be taken before the beetle offspring leave the infested tree. Thus, removing infested trees at the green attack stage is crucial for effective and timely forest management

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to minimise economic loss and prevent a massive outbreak (Fahse and Heurich, 2011). However, it is difficult to detect the early stage of the attack by the human eye since the trees are still green (Wulder et al., 2006). Traditionally, foresters perform field surveys looking for sawdust to identify infected trees during the early green-attack stage. Using such ground surveys is very laborious, and therefore, it is difficult to screen large areas for green attack and expensive (Abdullah et al., 2019b).

Alternatively, remote sensing observable plant traits that have a key role as indicators of vegetation stress can provide timely, accurate, and cost-effective information to finally mitigate and control bark beetle outbreaks. Since management of bark beetle attack requires a timely acquisition of high-resolution remote sensing data, airborne hyperspectral sensors and Unmanned Aerial Vehicles (UAVs) are ideal platforms. However, such data are too expensive to acquire data at a large scale and dense time series. Studying different stages of bark beetle attacks has revealed that the effects of bark beetles on trees (either spruce or pine) could be detected by remote sensing (Meddens et al., 2013; Filchev, 2012). Previous studies mainly focused on studying the effect of early Infestation on reflectance spectra by examining differences between healthy needles and those that have been under bark beetle green attack (Abdullah et al., 2019b; Meddens et al., 2013; Filchev, 2012; Coops et al., 2006, 2009; Cheng et al., 2010). A growing body of literature recognises the impact of early bark beetle infestation on the tree's optical properties (McDowell, 2011; Lawrence and Labus, 2003; Abdullah et al., 2019a, 2019c).

Chlorophyll is one of the plant pigments that provide valuable information about plant physiology and ecosystem processes (functions) enabling ecologists, and decision-makers to assess the influence of climate change and other anthropogenic and natural factors on plant functions and plants adaptation. Chlorophyll content (CCC) products retrieved from remote sensing data minimises the cost of in *situ* data collection and can profoundly address challenges in assessing ecosystems' health conditions, including water and nutrient stress caused by biological invasions such as bark beetle. It is only recently Abdullah et al. (2018) studied the effect of bark beetle infestation on the biochemical properties during the early stage and the spectral reflectance of Norway spruce needles in a temperate forest. These authors reported significant changes in the needles' biochemical and biophysical characteristics due to bark beetle infestation. These changes include alterations in CCC, water, dry matter, and nitrogen content (Fig. 1) (Abdullah et al., 2018, 2019b). However, it is still unknown whether early detection of the Infestation can be traced by quantifying canopy biochemical changes from remote sensing data. Hence, we hypothesis that CCC, which can be accurately retrieved from remote sensing (e.g., Peng et al., 2017; Darvishzadeh et al., 2012; Atzberger et al., 2010; Gitelson et al., 2005) can be used as a suitable proxy to discern healthy and bark beetle-infected spruce trees when there are no apparent visual symptoms in needles.

In this study, we aim to demonstrate the role of canopy chlorophyll content (CCC) derived from satellite remote sensing data through radiative transfer model (RTM) inversion to detect the stress and changes caused by European spruce bark beetles. Such a product may help to understand the Infestation dynamics and improve the management of bark beetle outbreaks in forest ecosystems over time. This study for the first time provides insights into the contribution of time series CCC satellite products retrieved from Sentinel-2 and RapidEye data for detecting bark beetle infestations.

2. Materials and methods

2.1. *Study area*

The study was conducted in the Bavarian Forest National Park (BFNP), which is located in south-eastern Germany along the border with the Czech Republic (Fig. 2). The Park is a mixed mountain forest with an approximate area of 240 km^2. Elevation varies between 600 m and 1453 m. The national Park has a temperate climate. Annual precipitation ranges from 1200 mm to 1800 mm, with average temperatures from 3 to 6 °C. The lower altitude (below 900 m a.s.l) section of the Park is dominated by brown soils, while in the high altitude area (above 900 m a.s.l), brown soils and brown podzolic soil are the dominant soil types (Heurich et al., 2010a).

There are three ecological zones: valleys, hillsides, and highlands. The natural forest ecosystems vary in each zone (Heurich et al., 2010a). Spruce forests dominate the valleys, mixed mountain forests on the hillsides and mountain spruce forests in the high elevations. The European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), and Fir (*Abies alba*) are the three dominant tree species (Cailleret, 2014). Due to massive disturbances by bark beetles and wind storms, the forest structure in the Park is very heterogeneous (Lehnert et al., 2013). Bark beetle attack only mature Norway spruce trees and, thus, this study is limited to the conifer and mixed stands of the Park (Fig. 2).

2.2. *Data*

2.2.1. *In situ CCC data*

The in situ data from healthy and infected trees were obtained during the field campaign in June and the beginning of July 2016 (Abdullah et al., 2019b). During this campaign, samples were collected in 40 randomly selected healthy plots and 21 plots with freshly infected trees. The infected trees were identified through an intensive field survey by looking for sawdust caused by beetle tunnels under the bark. Sample plots were 30 by 30-m size, and the location of each plot centre was measured using Leica GPS 1200 (Leica Geosystems AG, Heerbrugg, Switzerland) with an accuracy of better than 1 m after post-processing.

In each plot, sunlit needles were collected from three to five trees by

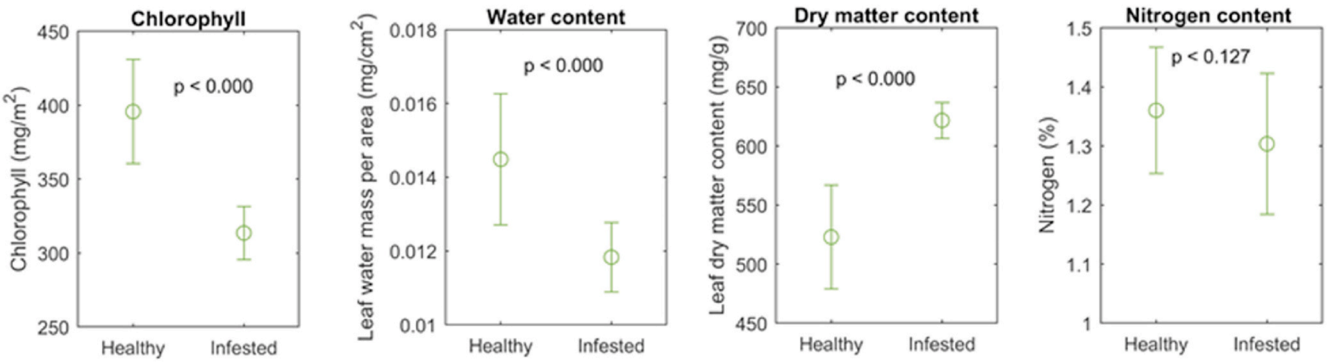

Fig. 1. Boxplot of plant traits alteration due to bark beetle infestation at the green attack stage. The box plots are based on in situ measurements obtained from 93 healthy and 63 infected trees (Source: Abdullah et al., 2019a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

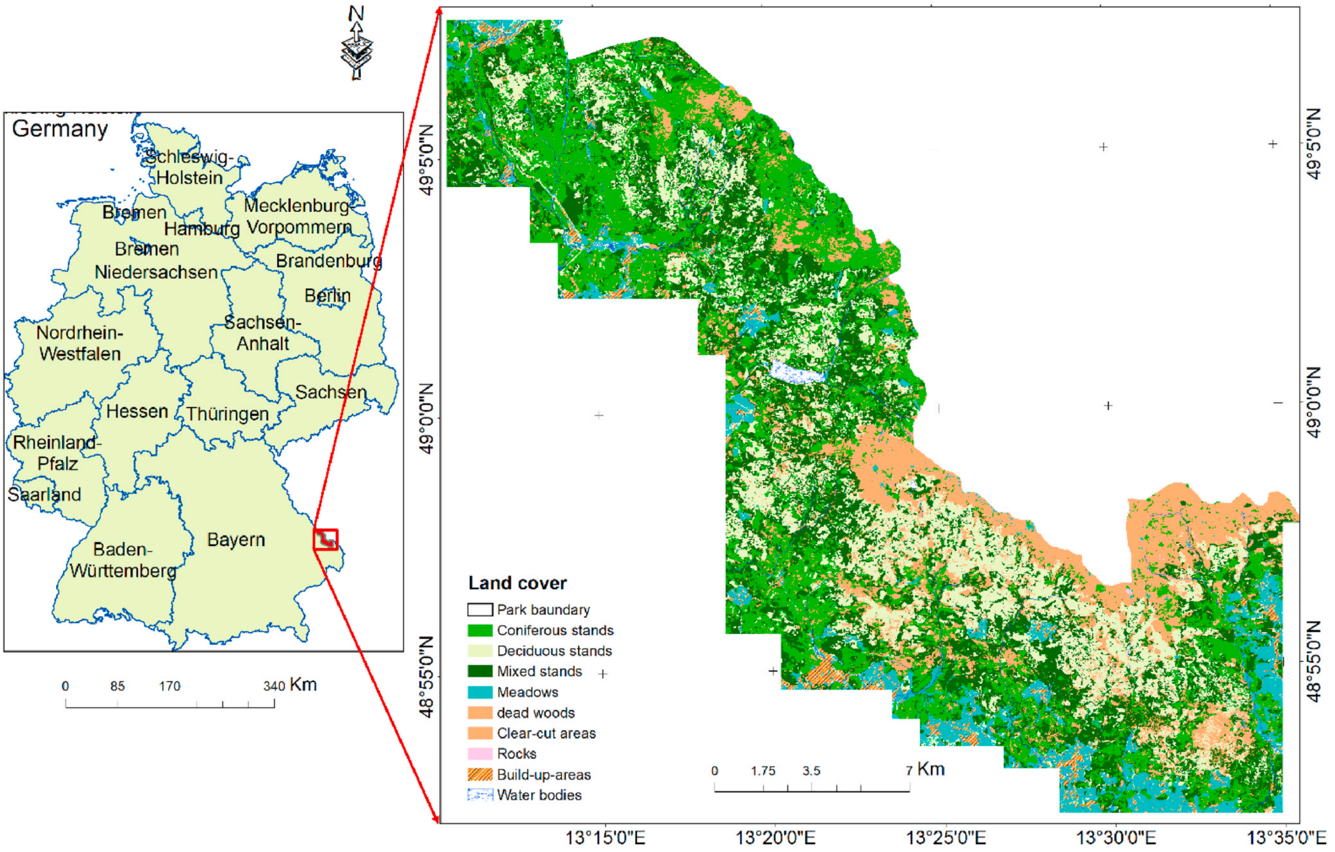

Fig. 2. Location and land cover map of Bavarian Forest National Park (Silveyra Gonzalez et al., 2018).

shooting branches from the trees' top layer with a crossbow's help. Leaf chlorophyll content of healthy and infected samples was measured using a CCM chlorophyll meter and averaged per plot. In situ leaf area index (LAI) measurement was conducted using Li-Cor LAI-2200 canopy analyser equipment (LI-COR, 1992). Finally, each plot's CCC was calculated by multiplying the plot's average leaf chlorophyll content and LAI. The summary of the in situ CCC records is presented in Table 1. Further details concerning the measurement protocols can be found in Abdullah et al. (2019a).

2.2.2. *Remote sensing data*

High spatial resolution multispectral images of RapidEye acquired in June/July 2011, 2013, and 2015 and Sentinel 2 images of June/July 2016, 2017, and 2018 were utilised. Remote sensing images with ≤20% cloud cover were not found for 2012 and 2014 and not considered in this study.

RapidEye is a five satellite constellation that provides high-resolution (5m) imagery in five bands (i.e., blue, green, red, red-edge and near-infrared). RapidEye L2A images covering the Park and its surrounding, which were systematically geo-corrected and orthorectified, were preprocessed for atmospheric and topographic correction using ATCOR and transformed to top of canopy (TOC) reflectance data. Finally, the RapidEye images were resampled into 20m by 20m cell size and utilised to map CCC products for 2011, 2013 and 2015.

Table 1
Summary statistics of the ground truth data collected in 40 healthy and 21 infected plots during the field campaign in 2016.

Statistics	LCC		CCC		LAI	
	Healthy	Infected	Healthy	Infected	Healthy	Infected
Minimum	31.3	17.4	0.94	0.64	2.36	1.27
Maximum	53.8	38.6	2.73	1.16	6.59	4.5
Mean	39.59	31.54	1.62	0.76	4.26	2.41
Std. Deviation	4.20	3.9	0.44	0.22	1.02	0.78

The standard Sentinel-2 Level-1C products of 2016, 2017, and 2018 were obtained from the European Space Agency's (ESA) Copernicus Open Access Hub. The images were atmospherically corrected using the Sen2Cor processor and transformed into Level-2A TOC reflectance data. Sentinel-2 has 13 bands between 443 and 2190 nm wavelength with spatial resolutions of 10m, 20m, and 60m. The spectral bands with 60m spatial resolution intended for coastal, water vapour and cirrus studies and were not utilised here. The remaining ten bands of Sentinel −2 TOC data were resampled to 20 m × 20 m cell size and used to retrieve CCC products for the three years.

The park administration undertakes aerial photograph acquisition campaigns every year and maps the location of infected trees through visual interpretation. Very high spatial resolution (0.1m) colour-infrared (VIS and NIR) aerial photographs are acquired yearly in June/July. Every year, the park administrators produce and distribute infestation maps from the interpretation of the colour aerial photographs by applying the object-orientated image analysis of Heurich et al. (2010b) for the semi-automatic detection of dead trees following a spruce bark beetle attack. These products were utilised to validate the stress (Infestation) maps derived from CCC. The remote sensing datasets used in this study are summarised in Table 2.

2.3. *Method*

The early stage bark beetle infestation mapping was undertaken using a hierarchical approach with a number of steps, including image selection and image processing, to produce maps and trend analysis.

Table 2
An overview of the different remote sensing datasets utilised for stress (bark beetle infestation) mapping and validation.

Data	Spatial resolution	Time period	No. of time steps	Notes
Sentinel 2 images	20m	2016–2018	June/July	Cloud free images acquired in June or July were used to generate the required R.S. based CCC
RapidEye images	5m	2011–2015	June/July	products of the pilot site.
Colour aerial photographs	0.1m	2012–2019	June/July	Used to validate the accuracy of the infestation maps

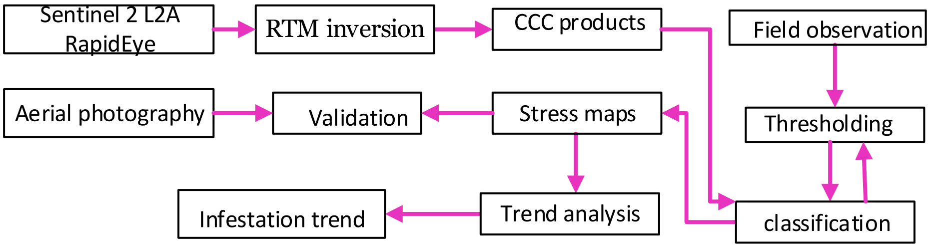

Fig. 3. Analytical framework of the stress (infestation mapping) using CCC products derived from remote sensing data.

Fig. 3 highlights the analytical framework of the study.

i) Generation of CCC products from Sentinel 2 and RapidEye images

The CCC products' generation was performed by inversion of the Invertible Forest Reflectance radiative transfer model (INFORM) (Schlerf and Atzberger, 2006, Atzberger, 2000) using the atmospherically corrected top of canopy reflectance spectra of Sentinel-2 and RapidEye images for the Bavarian forest national park. INFORM has shown to be a suitable RTM for retrieving biochemical properties in temperate mixed forest (Darvishzadeh et al., 2019; Ali et al, 2016, 2017, 2020; Wang et al., 2018). The INFORM model was inverted using a lookup table (LUT) approach. Two lookup tables were generated: one based on Sentinel-2, and the other was based on RapidEye sensors configurations. The inversion algorithm, which searches for the most accurate match between simulated and actual reflectance spectra, was applied to map CCC products from the Sentinel-2 and RapidEye images. Details of the INFORM input parameters, forward simulation to generate a LUT, and inversion of the model for the CCC's prediction can be found in Ali et al. (2020).

ii) Threshold determination

The threshold values that were used to classify the stressed (infected) and healthy (non-infected) pixels were approximated using the distribution of the CCC values in the calibration dataset (in situ CCC observations). To determine the threshold, the calibration data (obtained from field observations in 2016) were used (Table 1) to provide insights on where to place the threshold. Finally, infestation maps for each year were produced using the selected threshold value.

iii) Accuracy assessment

Visual image interpretations of colour aerial photographs acquired one year later (June/July) during post-infestation were used to validate the accuracy of the infestation maps generated in this study. For instance, reference data from interpretations of colour aerial photographs acquired in June 2016 were used to validate the stress map of 2015. Thus, the CCC based stress (Infestation) maps were compared to reference data obtained from processing and interpretation of the aerial photographs by independent experts from the Bavarian Forest National Park. The reference data (dead tree location due to Infestation) from aerial photography were in the form of polygons. Only plots dominated by bark beetle green attack (90%) that covered an area of $\geq$400 m^2 were selected, rasterised and resampled into 20 m × 20 m grid cells to match the cell size of the stress maps we produced (Table 3). Finally, a summary of the accuracy measures between the independent reference data and our infestation map products was computed, and the potential contribution of the CCC as derived from remote sensing data in detecting early-stage bark beetle infestation evaluated.

Table 3
Reference infestation data obtained from aerial photography interpretation and conversion to pixels.

Year	2011	2013	2015	2016	2017	2018
Total Infected pixels	629	283	248	408	348	713

3. Results

3.1. *CCC products from RapidEye and Sentinel 2*

Sample CCC products required for stress mapping, retrieved by the inversion of the INFORM on RapidEye and Sentinel 2 top of canopy reflectance, are presented in Fig. 4. We observed a significant variation in CCC products in space and time. Further, a high variation was observed in mixed stands where spruce and beech grow together. Fig. 5 illustrates the magnitude of CCC variation at four pixels with minimum and maximum values (range) in mixed and coniferous stands. Nonetheless, it is apparent that CCC products derived from RapidEye data

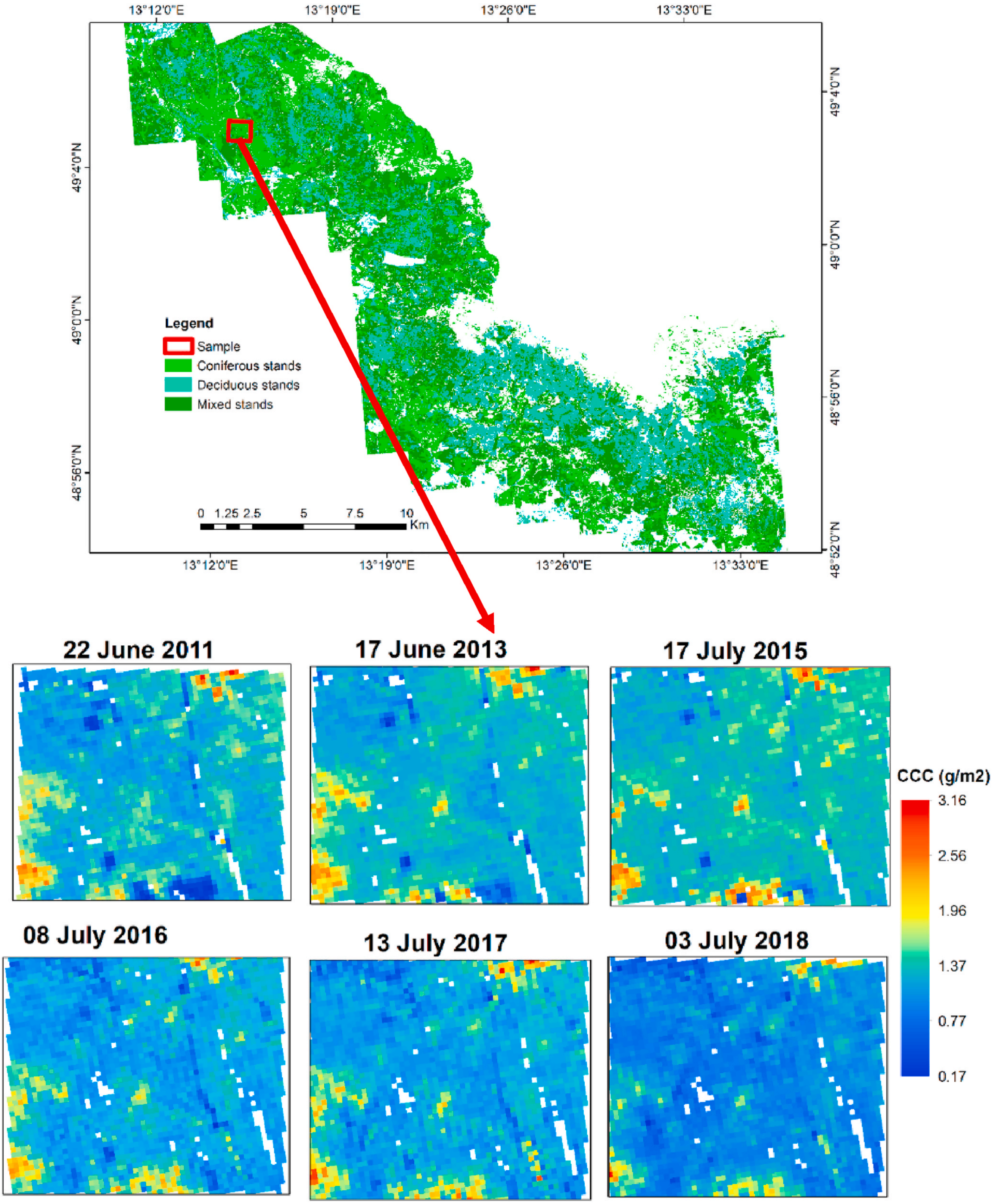

Fig. 4. Canopy chlorophyll content (CCC) distribution variability in space and time for RapidEye (2011–2015) and Sentinel-2 (2016–2018) at a sample mixed stand of Bavarian Forest National Park.

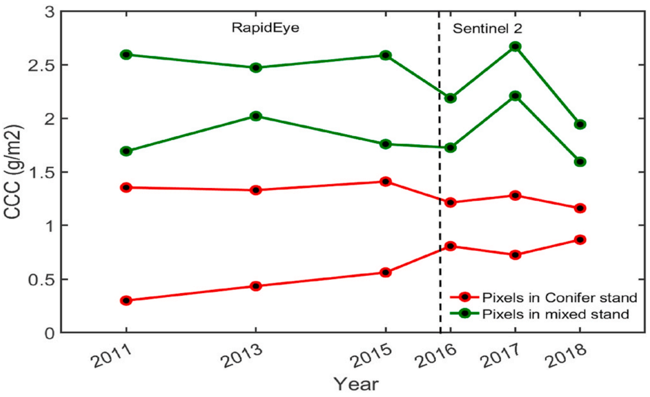

Fig. 5. Spatio-temporal variability of CCCamong mixed and coniferous stands (using minimum and maximum values, range) as derived from RapidEye and Sentinel-2 for the period 2011–2015 and 2016–2018, respectively. The higher CCC values for mixed stands (the top two lines) are due to the existence of beech trees.

(Figs. 4, 2011–2015) exhibit different patterns compared to the products derived from Sentinel 2 (Figs. 4, 2016–2018).

3.2. Stress (infestation) mapping

The thresholds for the three classes of the stress status maps (i.e., severely stressed, moderately stressed, and healthy) were fixed after observing the performance of the ground truth CCC ranges within one standard deviation. Sample maps of the six years' stress products are presented in Fig. 6. The products based on CCC threshold values show different stress levels over time (Fig. 7). The spatial distribution exhibits consistency in time. Specific sites with stress status in 2011 appeared stressed throughout the six years study period, although there are shifts between severely and moderately stressed status. Time-series trends of the imagery show small positive slopes that are significant ($p < 0.01$) (Fig. 8).

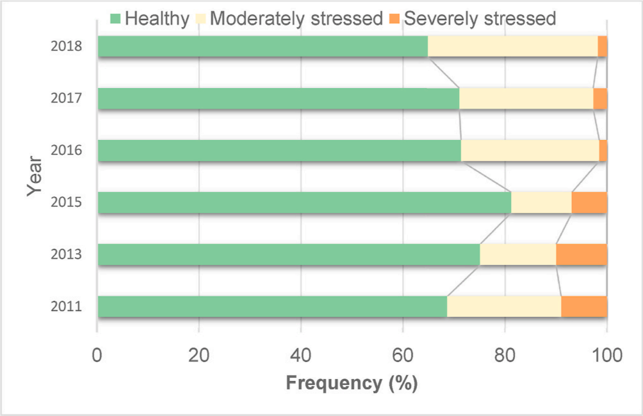

Fig. 7. Proportion of stressed and healthy vegetation in the Bavarian Forest National Park when CCC is used as a predictor.

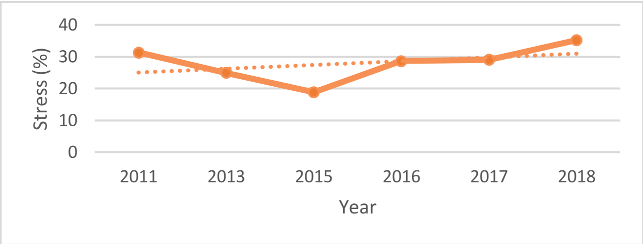

Fig. 8. Trend of (severely and moderately) stress detected using the plant trait-CCC throughout the Park. The broken line shows the trend of stress detected over time.

3.3. Validation

The accuracy of the classified products was validated using reference data acquired from image interpretation of the colour aerial photographs acquired one year later when the bark beetle-infected trees were dead (Fig. 9). For most years, a high proportion of the bark beetle-

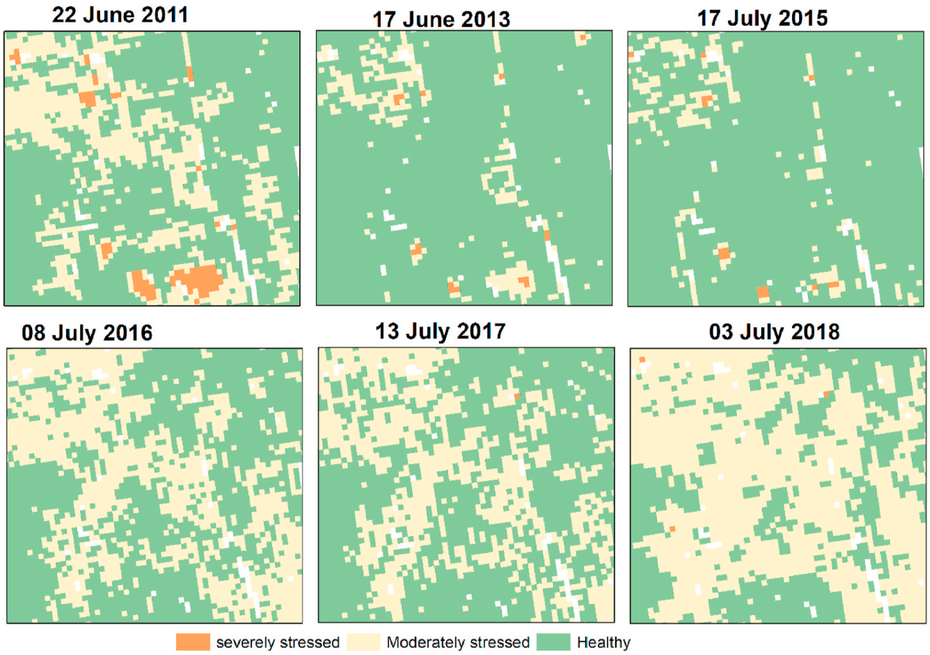

Fig. 6. Spatio-temporal distribution of vegetation stress in the Bavarian Forest National Park as predicted by CCC during the study period (2011–2018).

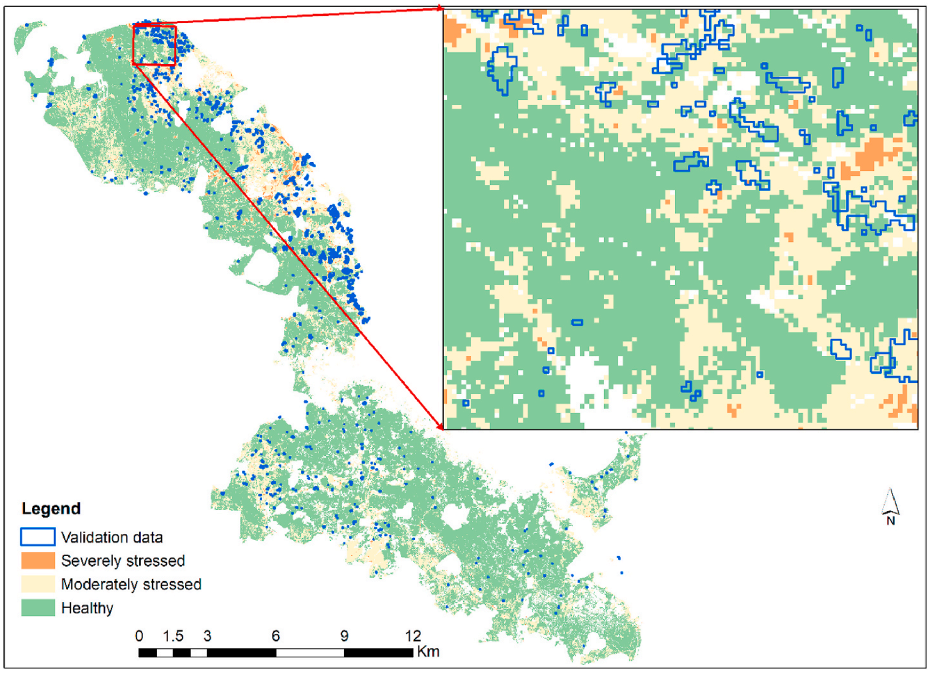

Fig. 9. Location of the bark beetle infestation reference data for 2016 overlaid onto the classified product using CCC as a predictor.

Table 4
Validation result of the stress maps classified using CCC as the predictor variable against the infestation reference data from aerial photographs' interpretation. All reference data are for bark beetle-infected trees located independently using field visits and experts' interpretation of aerial photographs.

Reference data (pixels)								
Year		2011	2013	2015	2016	2017	2018	Total
Stress maps	Severely stressed	153	63	51	22	14	57	360
	Moderately stressed	271	129	143	229	221	352	1345
	Healthy	205	91	54	157	113	304	924
	Total (pixels)	**629**	**283**	**248**	**408**	**348**	**713**	**2629**

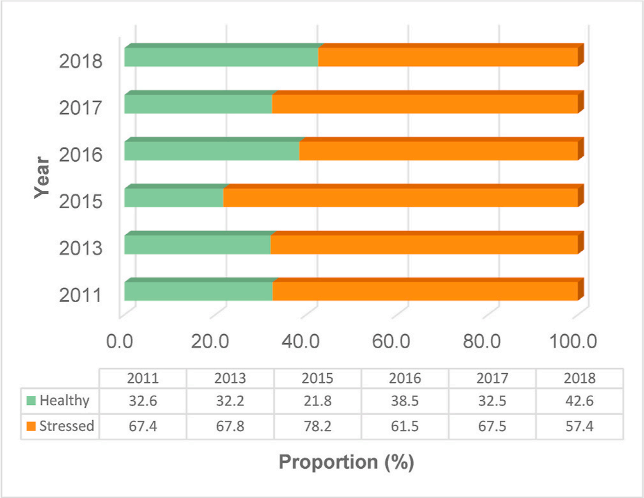

Fig. 10. Bar chart of the proportion of the bark beetle infestation (reference data) classified as healthy and (moderately and severely) stressed using CCC as a predictor.

infested trees identified through the aerial photographs' interpretation were either classified as severely or moderately stressed (Table 4 and Fig. 10). For 2016, a relatively weak agreement (409 from 713 pixels or 57.4%) was observed between the stress map derived from the CCC product and the reference data obtained from the Park, while the highest accuracy found in 2015 (194 from 248 pixels or 78.2%) (Table 4).

4. Discussion and conclusion

For the first time, this study utilise canopy chlorophyll products (CCC), retrieved from time-series satellite remote sensing data, for mapping and detecting stress caused by bark beetle attack. The study affirms the fact that a bark beetle attack causes a significant reduction in CCC that can be used to detect stress.

As illustrated in Figs. 4 and 5, inversion of the INFORM model for both the RapidEye and Sentinel 2 data enabled us to predict CCC variability in forest stands over time reliably. The bark beetle-infested trees are expected to exhibit relatively lower CCC values compared to healthy trees (Abdullah et al., 2019b). However, it is worth noting that the high CCC of beech trees compared to coniferous trees ((Fig. 5) substantially raised the CCC of pixels in mixed stands irrespective of the infestation state and this may have affected the accuracy of the stress classification in those stands. In future investigations, spectral un-mixing might be necessary to reduce the potential bias from broadleaf trees in mixed stands.

Very little information was found in the literature concerning the importance of satellite remotely sensed CCC for detecting stress-induced by pests and particularly by bark beetle attacks. The results of the stress (Infestation) mapping using satellite remotely sensed CCC as a predictor (Fig. 6) indicate that different stress levels with patterns have shown a slight (but highly statistically significant) trending over time (Fig. 8).

The stress mapping results, especially the early detection of stress, provide useful information for earliest opportunity planning for effective bark beetle management by forestry and conservation agencies.

Validation of stress maps against independent data (obtained from the expert visual interpretation of colour aerial photographs acquired annually) showed good classification accuracy (up to 78%) (Table 4 and Fig. 10), which confirms the significance of the canopy level variable for successful classification of stressed and healthy vegetation. Trees that were classified as healthy in our products, while identified as infected in the reference data (colour aerial photographs) might not necessarily be considered as errors, because of the time lag in the acquisition of the aerial photographs. In other words, some trees might appear healthy during the acquisition of the remote sensing data, but these trees were then infected later in the year prior to the acquisition of the colour aerial photographs in June/July one year later.

Nonetheless, our validation accuracy was comparable to (even better than) a number of recent studies examining the correlation between the change in spectral reflectance or their derivative and bark beetle infestation data. We predicted bark beetle induced stress using threshold values determined from in situ data of infected and healthy samples collected in 2016 and achieved an accuracy of up to 78.2%; other studies based on spectral reflectance analysis attained an accuracy of 67% in the same study area (Abdullah et al., 2019b). Another recent study by Latifi et al. (2018) using synthetic remote sensing time series obtained through fusion of MODIS and RapidEye data to map tree mortality due to bark beetle in the Bavarian Forest National Park found even lower accuracy ($R^2 \leq 0.54$).

Our results demonstrate those plant traits derived from remote sensing data, in particular CCC products, were rigorous in detecting bark beetle infestation and have a valuable role to play. Remote sensing-based CCC could subsequently be used for early warning of bark beetle outbreak and augment forest health assessment by successfully detecting large-scale spatiotemporal patterns of European spruce bark beetle. The findings in this study reaffirmed the key role of CCC in providing valuable information about plant physiology and ecosystem processes (functions), which can be used to assess the influence of natural factors (e.g., beetle infestation), climate change, and other anthropogenic factors on plant functions and plants adaptation. Thus, CCC's spatiotemporal dynamic products acquired from remote sensing can be used to measure the impact of bark beetle infestation.

However, it is worth noting that plant traits other than CCC may play a complementary role in detecting and fully understanding the bark beetle's infestation dynamics. Using additional plant traits such as dry matter and nitrogen content as a predictor may further improve early detection of bark beetle infestation using remote sensing.

Ethical statement

I testify on behalf of all co-authors that our revised article entitled "Canopy Chlorophyll Content Retrieved from Time Series Remote Sensing Data as a Proxy for Detecting Bark Beetle Infestation" which is submitted to Remote Sensing Applications: society and environment:

1) has not been published in whole or in part elsewhere;
2) the manuscript is not currently being considered for publication in another journal;
3) all authors have been personally and actively involved in substantive work leading to the manuscript, and will hold themselves jointly and individually responsible for its content.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2021.100524.

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