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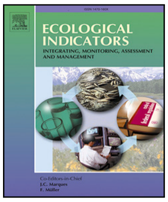

Original articles

Characterizing local forest structural complexity based on multi-platform and -sensor derived indicators

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ABSTRACT

Global climate change, biodiversity decline, and increasing disturbances are challenging the health and resilience of forests. In this regard, forest managers have sought to promote enhanced structural complexity (ESC) which utilizes the positive correlation between structural complexity and biodiversity or resilience to inform management practices. In light of these concerns, we integrated remote sensing data from multiple platforms and sensors to test the potential for quantifying different levels of structural complexity in temperate forests. This analysis was conducted in the context of the BETA-FOR project, where silvicultural manipulations of forest structure replicate silvicultural or natural disturbances. BETA-FOR includes a wide-range of standardized treatments across representative Central European broad-leaved forests, which are sub-divided into aggregated (gap felling) and distributed treatments (selective thinning) in combination with varying deadwood structures. This study provides a novel analysis of ESC from complementary remote sensing perspectives in order to bridge scales among structural complexity indicators. Remotely sensed observations comprise in-situ measurements (mobile and terrestrial laser scanning), as well as spaceborne observations from various sensors (including Sentinel-1 radar, Sentinel-2 multispectral, and GEDI lidar). We found moderate to strong inter-platform correlations among structural complexity metrics ($|r| >= 0.6$) between mobile laser scanning (box dimension, canopy cover), terrestrial laser scanning (canopy openness index), Sentinel-1 (VH, cross-polarized backscatter), Sentinel-2 (NMDI, Normalized Multi-band Drought Index), and GEDI (total canopy cover). In addition, multivariate analyses revealed that ESC of gap aggregated treatments can be effectively delineated from control and distributed treatments across all considered remote sensing sensors/platforms. Therefore, the metrics from different platforms and sensors better characterize the changes in structural complexity through aggregated compared to distributed treatments. Furthermore, we identified the sensitivity of in-situ and spaceborne metrics towards the presence of standing deadwood structures. An unsupervised clustering analysis highlights distinct differences in structural complexity of aggregated treatments with snags and habitat trees compared with aggregated treatments without standing structures, as well as distributed and control treatments. Findings demonstrate the potential of various sensors and platforms for monitoring forest structural complexity. We recommend the spaceborne indicators Sentinel-1 VH cv, Sentinel-2 NMDI cv, and GEDI cover cv to monitor ESC at high spatio-temporal resolution as they show highest correlations to in-situ metrics, thus holding the potential to guide adaptive forest management.

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1. Introduction

Forest structure has been identified as an indicator of forest biodiversity and ecosystem functioning (Bohn and Huth, 2017; Heidrich et al., 2020). Since in-situ measurements of biodiversity and ecosystem functioning are challenging to assess and time-consuming to measure, an increasing number of studies have suggested measuring forest structure as a surrogate for these latent variables (Gao et al., 2014; Lelli et al., 2019; Storch et al., 2018). In primary forests, structural complexity has important implications for potential functional diversity (species richness and complementary of crown architectures, Zheng et al. (2023)), physiological tolerance (shade tolerance, Valladares and Niinemets (2008)), and maximum tree size (hydrolic limitation hypothesis, Klein et al. (2015), Ryan et al. (2006)). High forest structural complexity is closely linked to increased rates of biodiversity (Coverdale and Davies, 2023; Hakkenberg and Goetz, 2021; Heidrich et al., 2020; Knuff et al., 2020; Ray et al., 2023), as well as improved resilience towards climate change induced disturbances (Lecina-Diaz et al., 2024; Ma et al., 2023; Seidel and Ammer, 2023).

Forest structure and its relationship to biodiversity has been investigated in many fields of environmental research: the review of Coverdale and Davies (2023) found a general positive relationship of plant diversity and structural complexity. The study of Gough et al. (2019) identified increased rates of net primary production in structurally complex temperate forests in the United States across sites of the National Ecological Observatory Network (NEON). Other studies clearly showed that primary forests were more complex than managed forests, even when management focused on structural complexity (e.g. Stiers et al. (2018)). An explanation of the observed pattern based on principles of thermodynamics was proposed to deeper investigate the relationship between structural complexity, productivity, and adaptability of forests (Seidel and Ammer, 2023). Furthermore, links between multi-layering of the canopy and insect abundance were confirmed by both Knuff et al. (2020) (mixed temperate forests in Germany) and Müller et al. (2018a) (European beech dominated forests in Germany). In addition to the ability of structurally complex forests to host increased biodiversity, further ecosystem properties emerge from the interaction of structure and disturbance (Hilmers et al., 2018; Mitchell et al., 2023). For example, Gough et al. (2022) identified complex interactions between structural complexity and disturbance in temperate forests of Michigan, United States, which stress the necessity of further studies for a more comprehensive understanding of modified trajectories of structural complexity through disturbance.

Human activities, such as land-use intensification, deforestation, and urbanization have altered the natural patterns of forest structure globally towards simplified forest structural complexity (Ehbrecht et al., 2021; Li et al., 2023; Sabatini et al., 2018). In Central Europe, multiple consecutive drought years of previously unseen duration and intensity (Buras et al., 2020, 2021; Rakovec et al., 2022; Schuldt et al., 2020) have caused excess forest mortality (Senf et al., 2020a). Increasing tree mortality due to drought conditions has been found not only for non-native species (e.g. secondary Norway spruce plantations, Jandl et al. (2019)), but also for the naturally dominating tree species European beech (Rukh et al., 2023). To sustain forest health and to cope with climate change events in the future, enhancement of structural complexity (ESC) within forest patches and between forest patches seems one promising way to encourage forest resilience beyond greater tree species diversity (Müller et al., 2018b).

Remote sensing has been identified as a key method for continuous monitoring of forest structure from local to global scales (Camarretta et al., 2020; Jetz et al., 2016; Skidmore et al., 2021). The characterization of local-scale forest structural complexity through in-situ measurements focuses on the analysis of individual tree structures to stand level (Morsdorf et al., 2018). Active sensors (e.g. mobile and terrestrial laser scanning, or MLS and TLS, respectively) enable the calculation of dense three-dimensional point clouds to relate structural complexity to forest management, tree species diversity, and microclimate (Ehbrecht et al., 2017). Besides the measurement of stand structural complexity (Seidel, 2018), specific vertical vegetation layers (Ehbrecht et al., 2016), and understory vegetation can be identified and characterized (Willim et al., 2019, 2020). The sub-canopy perspective of in-situ measurements holds complementary but distinct information on structural complexity compared to airborne and spaceborne sensors which cannot penetrate the canopy (e.g. optical sensors) or assess sub-canopy structure more generally (Atkins et al., 2020). UAS (unoccupied aerial systems) and aircraft-based remote sensing come with the benefit of analyzing larger areas with the option of parallel multi-sensor acquisitions (Müllerová et al., 2021; Mura et al., 2015). LaRue et al. (2020) identified strong univariate relationships of various measurements of forest structure and structural complexity based on TLS and airborne laser scanning (ALS). Measurements of structural complexity from ALS data were shown to relate to forest age, ground-based complexity measures, management intensity as well as microclimate (Seidel et al., 2020). Further applications of ALS include the analysis of diversity in canopy height (Senf et al., 2020b) and characterization of old-growth structures (Martin and Valeria, 2022).

The application of spaceborne remote sensing for forest structure analysis has mainly focused on the modeling of individual forest structure attributes at national to continental scale (e.g. Coops et al. (2021)), rather than investigating structural complexity through the combination of various structural attributes. With the availability of novel spaceborne samples of forest structure derived from the Global Ecosystem Dynamics Investigation (GEDI) sensor, wall to wall maps of canopy height, canopy cover, and biomass have been generated based on machine and deep learning regression models (Kacic et al., 2021, 2023; Lang et al., 2023; Potapov et al., 2021; Rishmawi et al., 2022). Atkins et al. (2023b) and Hakkenberg et al. (2023) each found scale-dependencies of lidar metrics for characterizing structural complexity, concluding that the appropriate scale depends on the targeted structural element and forest type. Further innovative applications of spaceborne lidar include the calculation of compound indicators based on complementary attributes of forest structure for assessing structural density (Li et al., 2023), tree canopy height heterogeneity (Torresani et al., 2023), as well as the analysis of non-tree plant diversity in order to investigate generalized biodiversity-structure relationships (Hakkenberg et al., 2023). In addition, Schneider et al. (2020) demonstrated that simulated GEDI canopy height, density and layering data has a similar potential to ALS for the prediction of functional richness.

Previous conceptual studies on forest structural complexity have provided different definitions of structural complexity. The pioneering review by McElhinny et al. (2005) delineated forest and woodland structures into structural attributes and stand structure, supporting the use of structural complexity instead of structural diversity for the description of stand structure characteristics. The authors considered structural diversity to be a single metric not capturing the complete diversity explaining biological diversity. In contrast, the recent study by LaRue et al. (2023) which framed the concept on ecological findings of three-dimensional characteristics and structural diversity, proposed to treat structural diversity, structural heterogeneity, and structural complexity as synonyms. In the present study, we summarized various forest structural attributes under the term “structural complexity” although the calculated metrics measure different structural attributes: forest canopy cover, vertical heterogeneity, vertical area and density, structural complexity, or vertical and horizontal structural heterogeneity (please see categorization of structural attributes according to Atkins et al. (2023a), Table 1). Nevertheless, we provide further details on the different structural attributes and derived metrics in section “2. Materials and Methods”, and consider the correlated and complementary information from each metric when interpreting the results.

This study assesses cross-scale monitoring of in-situ and spaceborne metrics of forest structural complexity to bridge costs and benefits

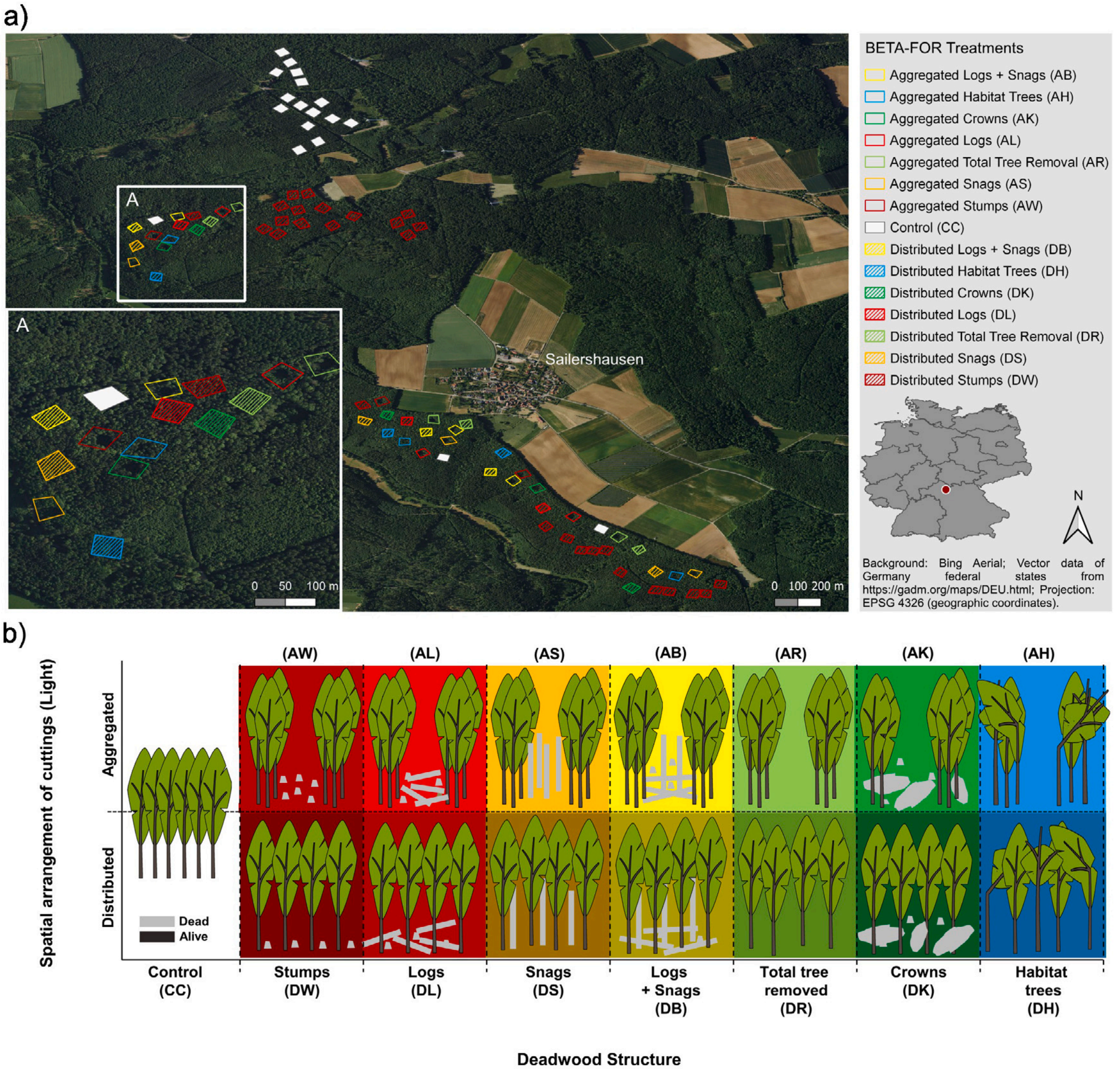


Fig. 1. Map of the study area (a) and schematic figure of BETA-FOR treatments (b). The schematic figure (adapted from Mueller et al. (2022a)) presents different deadwood structures (x-axis) and spatial arrangements of cuttings (y-axis).

among different remote sensing platforms. Furthermore, we provide novel insights on understudied research goals through the assessment of various indicators of structural complexity in close connection to adaptive silvicultural management. This analysis is embedded in the interdisciplinary research project “BETA-FOR” which focuses on ESC through experimental silvicultural manipulations in German broad-leaved forests (Mueller et al., 2022b). BETA-FOR investigates structural complexity in a diverse network of patches comprising different light conditions (aggregated and distributed cuttings) and deadwood management types (total deadwood removal, remaining stumps, downed and standing deadwood, habitat trees, Mueller et al. (2022a)). The controlled experimental design, as well as the availability of data on structural complexity from various platforms and sensors, namely MLS, TLS, Sentinel-1 (radar satellite), Sentinel-2 (multispectral satellite), and GEDI (spaceborne lidar, Light detection and ranging), offer unique opportunities to address the following research goals: (a) a cross-scale comparison of in-situ to spaceborne observations to support the identification of indicator suites for monitoring and scale-specific management decision making; (b) a comparison of two popular satellite sensors for vegetation analysis in addition to novel spaceborne lidar data to improve our understanding of forest structural complexity measured as surface roughness or water content (Sentinel-1), photosynthetic activity (Sentinel-2), and three-dimensional structure (GEDI); (c) determining the ability of experimental silvicultural treatments to provide insights on forest structural complexity along a gradient of deadwood structural complexity (from no deadwood to combined downed and standing deadwood), and contrasting light conditions (aggregated and distributed cuttings).

This study tests the following hypotheses: (1) There are moderate to strong intra- (MLS | TLS | spaceborne) and inter-platform (MLS & TLS & spaceborne) correlations between different variables of forest structural complexity. (2) Across all platforms, remotely sensed metrics of forest structure accurately delineate aggregated treatments (major increase in structural complexity due to gap creation) from distributed (selective thinning) and control treatments. (3) The difference in structural complexity of aggregated to distributed and control treatments can be assessed through unsupervised clustering since aggregated treatments are characterized as possessing the highest level of structural complexity.

2. Materials and methods

2.1. Study area

The study area is located in Central Germany (Haßberge, north of Steigerwald), within a forest area belonging to the Julius-Maximilians-University of Würzburg (Fig. 1(a)). These forests are intensively managed and comparatively species rich in terms of broad-leaved tree species, with high proportions of European Ash (Fraxinus excelsior), European Beech (Fagus sylvatica), European Hornbeam (Carpinus betulus), Maple (Acer spec.) and Oak (Quercus spec.) species (Mueller et al., 2022b). The study area, also called "University Forest", serves as a focal region of the interdisciplinary research project "BETA-FOR". BETA-FOR experimental silvicultural manipulations were conducted in November and December 2018 to study the effect of ESC on biodiversity (Mueller et al., 2022a). For six patches (AK: n=1, DW: n=6) there was no data of MLS and TLS due to complications during data acquisition. Therefore, the present study focuses on 84 patches for which data from both MLS and TLS was available, taken under leaf-on conditions in 2023. There are three patches each for all aggregated and distributed treatments, except for AK (n=2) and DW (n=28). In addition, there are 18 control treatments.

The schematic figure (Fig. 1(b)) presents BETA-FOR treatments which comprise a wide range of deadwood structures (x-axis) in two spatial arrangements of cuttings (aggregated and distributed treatments, y-axis). In addition, control treatments were established as a reference for unaltered forest structure conditions. In each square patch (50 m × 50 m), about 30 % of the patch's tree biomass was manipulated. Aggregated treatments are characterized by increased structural complexity through aggregated cuttings producing a centered gap with a diameter of 30 m, i.e. no manipulation in the outer patch area. Distributed cuttings were conducted in the complete patch area of distributed treatments. The gradient of deadwood structures from total tree removal, stumps remaining, logs (downed deadwood), crowns, snags (standing deadwood), logs and snags, to habitat trees (tilting of trees, damages on bark, creating caves) mimics various silvicultural management practices of complete tree removal and generation of old-growth structures, promoting biodiversity for different taxonomic levels (bats: Hendel et al. (2023), Kortmann et al. (2018), Rigo et al. (2024), Singer et al. (2021), beetles: Müller et al. (2014), birds: Rigo et al. (2024), Singer et al. (2021), epigeal arthropods: Seibold et al. (2016a), insects: Staab et al. (2023)).

2.2. Remote sensing data

The present study analyzes forest structural complexity based on various remote sensing sensors and platforms, integrating several metrics from MLS, TLS and spaceborne remote sensing to assess different attributes of forest structure corresponding to Atkins et al. (2023a). Table 1 provides an overview of MLS, TLS, Sentinel-1, Sentinel-2, and GEDI metrics.

2.2.1. Mobile laser scanning data

MLS data was measured in July 2023 (leaf-on) in 84 patches. A ZEB Horizon hand-held mobile laser scanner (Geoslam Ltd., UK) was carried through each stand by starting at the patch center and walking in concentric circles of slowly increasing radius, surrounding the center between 5 and 10 times, depending on stand density, until the entire patch area was scanned. Then the device was carried back to the center and the recording was stopped. The following attributes of forest structure were derived at patch-level: structural complexity (box dimension, Seidel (2018)), canopy coverage (canopy cover, Höwler et al. (2024)), vertical heterogeneity (foliage height diversity, according to MacArthur (1965), MacArthur and Horn (1969) as in Seidel et al. (2016)), and vertical area and density (effective number of layers: ENL of Hill numbers 0, 1, 2; evenness; Ehbrecht et al. (2016)). Seidel (2018) introduced the calculation of the box dimension in the context of single tree architectural analysis. Further studies identified architectural characteristics of single trees that have strong influence on structural complexity (Seidel et al., 2019b,a). Later, the approach was extended for a stand level complexity assessment and demonstrated sensitivity towards structure related properties such as stand age, management intensity (Seidel et al., 2020; Camarretta et al., 2021), forest vitality (Heidenreich and Seidel, 2022), or management type (Neudam et al., 2022). Canopy cover was calculated by applying a 20 cm-voxelization to the point clouds and determining the percentage of 20 × 20 cm ground cells covered by one or more voxels above the same x-y-cell (Höwler et al., 2024). Both metrics on ENL and evenness measure the space occupied by vegetation in a stand. Ehbrecht et al. (2016) conducted a comprehensive analysis across three well-known research sites in Germany (Biodiversity Exploratories), and successfully distinguished different management stands based on ENL. In addition, correlations of ENL to basal area, quadratic mean diameter, stem density and stand age were identified.

2.2.2. Terrestrial laser scanning data

Terrestrial laser scans were conducted in August 2023 (leaf-on) at all BETA-FOR patches considered for analysis (84 patches). We conducted a laser scan in single-scan mode in the center of each patch using a FARO M70 terrestrial laser scanning (Faro Technologies Inc., Lake Marry, USA). Two patch-level metrics on structural complexity (stand structural complexity index, SSCI; understory complexity index, UCI) were calculated, as well as canopy openness (canopy openness index, COI). The SSCI quantifies structural complexity based on fractal dimension and has been widely used in recent years (Ehbrecht et al., 2017; Frey et al., 2019; Ehbrecht et al., 2021; Perles-Garcia et al., 2021; Zemp et al., 2023). Willim et al. (2019) revealed that the UCI is strongly driven by tree regeneration, while holding significant relationships to tree basal area and canopy openness (Seidel et al., 2021). COI was quantified to delineate open and closed canopies (Zheng et al., 2012).

2.2.3. Spaceborne remote sensing data

According to the classification of forest structural attributes by Atkins et al. (2023a), spaceborne derived metrics to characterize structural heterogeneity include roughness and water content (Sentinel-1, radar), photosynthetic activity (Sentinel-2, multispectral), and vertical and horizontal structure (GEDI, lidar). Kacic et al. (2024) analyzed Sentinel-1 and Sentinel-2 time-series in the BETA-FOR region "University Forest" based on a comprehensive catalogue of spectral indices. Specific metrics (a combination of spectral index and spatial statistic at patch-level) were identified by assessing the treatment implementation event (change in forest structural complexity) through Bayesian time-series decomposition (BEAST, Bayesian Estimator of Abrupt change, Seasonal change, and Trend, Zhao et al. (2019)). The metrics Sentinel-1 VH cv (coefficient of variation, [db]) and Sentinel-2 NMDI (Normalized Multi-band Drought Index, unitless, Wang and Qu (2007)) cv were the best metrics of each sensor assessing the treatment implementation event. Therefore, we used the patch-level time-series metrics from Sentinel-1 VH cv and Sentinel-2 NMDI cv from 2016 to 2023 in the present study as complementary spaceborne proxies of structural complexity. To assess the dynamics of forest structural complexity as a multi-annual time-series (2016–2023) based on Sentinel-1 and -2, we calculated temporal aggregations (annual median per patch for the months from July to September) in order to represent average summer conditions. Please note that the calculation of the cv (e.g. Abdi (2010)) for pre-processed Sentinel-1 GRD (Ground Range Detected, unit: db) data results in negative values since the original pixel values are typically negative in forests. For a comparative analysis of Sentinel-1 VH cv with other spaceborne cv measures of forest structural heterogeneity, we calculated the cv of Sentinel-1 VH using the absolute value of the patch-level mean. Therefore, we derive positive values for Sentinel-1 VH cv for simplified cross-comparison with the other positive spaceborne cv measures.

In addition, we integrated continuous forest structure information through modeled GEDI samples (n=15,000 per year and forest structure attribute) based on Sentinel-1 and Sentinel-2 spatio-temporal composites for Germany by Kacic et al. (2023). The modeling approach (random forest regression) was also adopted for Sentinel-1 and Sentinel-2 spatio-temporal composites from 2023 in combination with GEDI samples spanning the period of June to September of 2022 (GEDI data is only available until March 2023, i.e. not available for summer 2023) to model canopy height, total canopy cover, and above-ground biomass

Table 1
Overview of remote sensing metrics on structural complexity.

Sensor, platform, year	Metrics	Metrics classification by Atkins et al. (2023a)	Citation
MLS, mobile laser scanning, handheld, 2023	box dimension, canopy cover, foliage height diversity, effective number of layers (ENL), evenness	structural complexity (box dimension), cover and openness (canopy cover), vertical heterogeneity (foliage height diversity), vertical area and density (ENL, evenness)	Seidel (2018), Höwler et al. (2024), Seidel et al. (2016), Ehbrecht et al. (2016)
TLS, terrestrial laser-scanning, tripod-based, 2023	stand structural complexity index (SSCI), understory complexity index (UCI), canopy openness index (COI)	structural complexity (SSCI, UCI), cover and openness (COI)	Ehbrecht et al. (2017), Willim et al. (2019), Zheng et al. (2012)
Sentinel-1, radar satellite, 2016–2023	VH (vertical-horizontal polarization) coefficient of variation (cv)	heterogeneity of surface roughness and moisture	Kacic et al. (2024)
Sentinel-2, multispectral satellite, 2016–2023	NMDI (Normalized Multi-band Drought Index) cv	heterogeneity of photosynthetic activity with sensitivity to drought stress	Kacic et al. (2024)
GEDI, spaceborne lidar; Sentinel-1, radar satellite; Sentinel-2, multispectral satellite; 2017–2023	rh95 (canopy height) cv (coefficient of variation), cover (total canopy cover) cv, agbd (above-ground biomass density) cv	heterogeneity of vertical and horizontal forest structure (rh95, agbd); cover and openness (cover); modeling of GEDI samples based on Sentinel-1 and Sentinel-2 composites	Kacic et al. (2023)

density for 2023. The model accuracy for 2023 was similar to previous years (2017 to 2022) amounting to Mean-Absolute Errors (MAE) of 5.09 m (canopy height), 16.00% (total canopy cover), and 45.43 Mg/ha (above-ground biomass density). Derived metrics for different forest structure attributes, namely canopy height (rh95, 95th percentile of the relative height metrics, [m]), total canopy cover (cover, [%]), and above-ground biomass density (agbd, [Mg/ha]), were aggregated for each year (summer conditions, 2018 to 2023) as individual patch-level metrics (cv). The derived metrics for each patch characterize the heterogeneity of canopy height, total canopy cover, and above-ground biomass density.

2.3. Statistical analyses

In order to assess linear statistical relationships between MLS, TLS, and spaceborne metrics of forest structural complexity, we carried out correlation analyses. Bivariate Pearson correlation coefficients (r) were calculated among all metrics and are visualized as a heatmap and a correlation network to identify intra- and inter-platform relationships (hypothesis (1)).

Multivariate comparisons of cross-scale metrics of forest structural complexity visualized as radar plots serve as dissimilarity analysis of the BETA-FOR treatment groups: control, aggregated, and distributed. The standardized scaling of all metrics to [0,1] – with values close to 0 indicating low structural complexity and values close to 1 indicating high structural complexity – enables direct comparisons among different metrics in order to identify metrics best delineating the different treatment groups (hypothesis (2)).

We implemented an unsupervised clustering analysis (K-Means) of various forest structural complexity metrics to test if the BETA-FOR patches can be assigned to the respective treatment groups (control, distributed, aggregated) when n = 3 clusters are specified (hypothesis (3)). We applied an iterative randomized clustering to initialize different centroid seeds. To assess platform-dependencies, the clustering analysis was conducted as platform-specific (separate for each platform) and across-platforms (pooling all metrics).

3. Results

This study aims to assess forest structural complexity from multiple remote sensing platforms and sensors to understand relationships among different metrics and to identify suitable spaceborne indicators of ESC. We sought to characterize each platform (MLS, TLS, spaceborne) as comprehensively as possible through the inclusion of multiple metrics of MLS (box-dimension, canopy cover, ENL, evenness, foliage height diversity), TLS (SSCI, UCI, COI, supplementary material B), and spaceborne remote sensing (Sentinel-1 VH cv, Sentinel-2 NMDI cv, GEDI rh95 cv, GEDI cover cv, GEDI agbd cv) (Table 1). Since not all metrics delineated differences in structural complexity among the BETA-FOR treatments (e.g. MLS-based ENL, evenness, and foliage height diversity) those metrics are not shown in the following figures (see supplementary material A). Nevertheless, all available metrics were integrated in the analysis to enable a comprehensive assessment of structural complexity in order to thoroughly assess the general potential of each platform and sensor.

3.1. Spaceborne time-series of individual BETA-FOR treatments

Multi-annual spaceborne time-series characterize pre- and post-disturbance forest structural complexity at the patch-level based on Sentinel-1 VH cv, Sentinel-2 NMDI cv, and GEDI cover cv data. By disturbance we refer to the ESC treatment implementation event from November to December 2018.

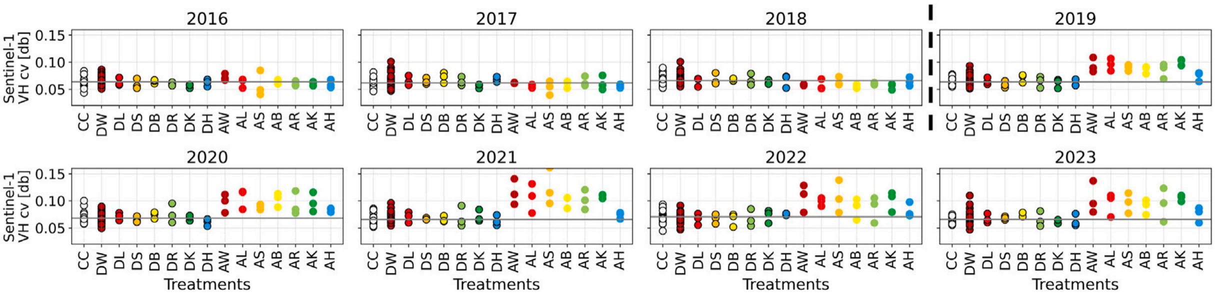


Fig. 2. Sentinel-1 VH coefficient of variation (cv) time-series at patch-level of individual BETA-FOR patches from 2016 to 2023. A single point represents the structural complexity of a patch. The color-coding follows the schematic representation of BETA-FOR treatments in Fig. 1. The black contours of points for control and distributed treatments indicates the difference in structural complexity to aggregated treatments (no contours). The horizontal gray line in each plot shows the respective mean of control treatments (CC). The dashed vertical line represents the treatment implementation event in November to December 2018.

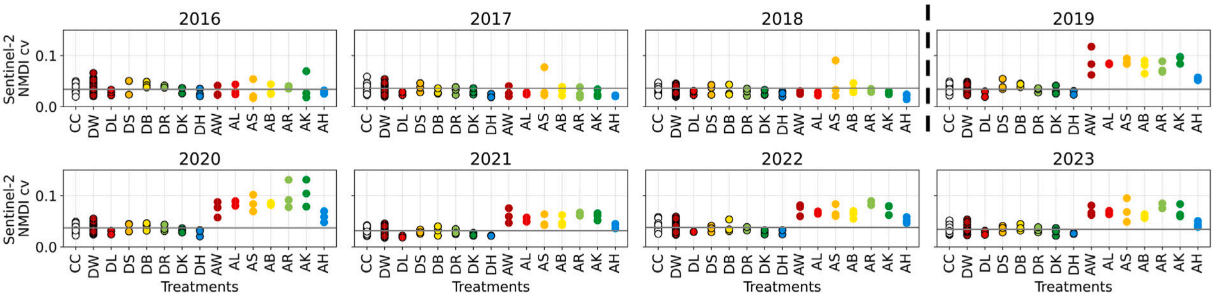


Fig. 3. Sentinel-2 NMDI coefficient of variation (cv) time-series at the patch-level of individual BETA-FOR patches from 2016 to 2023. A single point represents the structural complexity of a patch. The color-coding follows the schematic representation of BETA-FOR treatments in Fig. 1. The black contours of points for control and distributed treatments indicates the difference in structural complexity to aggregated treatments (no contours). The horizontal gray line in each plot shows the respective mean of control treatments (CC). The dashed vertical line represents the treatment implementation event in November to December 2018.

3.1.1. Sentinel-1

The Sentinel-1 VH cv time-series from 2016 to 2023 characterizes the pre- (2016 to 2018) and post-disturbance (2019 to 2023) forest structural complexity. The pre-disturbance conditions indicate similar structural complexity among all BETA-FOR patches (Fig. 2). After the treatment implementations in November and December 2018, post-disturbance conditions show increased structural complexity for aggregated treatments. Except for the aggregated habitat trees treatment (AH), increased structural complexity can be characterized by Sentinel-1 VH cv values close to 0.1. In addition, the variance per aggregated treatment type, i.e. among individual patches of the same treatment, increases over time. Control and distributed treatments are characterized by constant conditions from 2016 to 2023 and lower variance among treatments and within patches of identical treatment type.

3.1.2. Sentinel-2

The Sentinel-2 NMDI cv time-series for each BETA-FOR patch was temporally aggregated in the same way as Sentinel-1 data (see Section 2.2.3). Similarly, the post-disturbance conditions for aggregated treatments show increased structural complexity compared to previous years, as well as control and distributed treatments (Fig. 3). The AH treatment represents an exception to the general pattern observed, possessing lower structural complexity in comparison to the other aggregated treatments, i.e. more similarity in structural complexity to control and distributed treatments.

3.1.3. GEDI

Fig. 4 presents the annual data on GEDI-derived cover cv from 2018 to 2023. The pre-disturbance conditions in 2018 do not show differences among the BETA-FOR patches (all values lower than 0.15). In 2019, different levels of forest structural complexity among the treatment groups are apparent, with most aggregated treatments possessing increased structural complexity (values greater than 0.2). Similar to the findings based on Sentinel-1 and Sentinel-2, the AH treatment patches are characterized by lower structural complexity compared to the other aggregated treatments. From 2020 to 2023, a decline in structural complexity for aggregated treatments (except AH) can be observed. See supplementary material C for the time-series for GEDI agbd cv, and GEDI rh95 cv.

3.2. Correlation analysis

The analysis of bivariate correlations among cross-scale metrics of forest structural complexity for the year 2023 shows moderate to strong correlations across metrics of the same and different platforms (Fig. 5(a)). Relationships among MLS-derived metrics are highly correlated (box dimension, canopy cover, r = 0.9). The TLS metrics (COI, SSCI, UCI) indicate, on the one hand, weak positive correlations (COI and SSCI to UCI, r <= 0.3), and on the other hand, moderate negative correlations (COI and SSCI, r = −0.6). The spaceborne metrics hold moderate to strong positive correlations (Sentinel-1 VH cv, Sentinel-2 NMDI cv, GEDI agbd cv, GEDI cover cv, GEDI rh95 cv, r >= 0.5). There are moderate to strong positive and negative correlations (|r| >= 0.6) among the following metrics across-platforms: MLS (box dimension, canopy cover), TLS (COI), spaceborne metrics (Sentinel-1 VH cv, Sentinel-2 NMDI cv, GEDI cover cv). Moderate positive and negative correlations cross-scales (|r| >=0.4 and |r| <= 0.6) were found for MLS (box dimension, canopy cover), TLS (SSCI, UCI), and spaceborne metrics (Sentinel-1 VH cv, Sentinel-2 NMDI cv, GEDI agbd cv, GEDI rh95 cv). The negative correlations of MLS metrics and spaceborne metrics result from the fact that MLS metrics are inverse to spaceborne metrics, with the first quantifying complexity and the latter addressing heterogeneity.

The correlation network (Fig. 5(b)), filtered to |r| > 0.5, highlights the moderate to strong correlations found across-platforms. The close proximity of metrics indicates a high number of strong correlations.

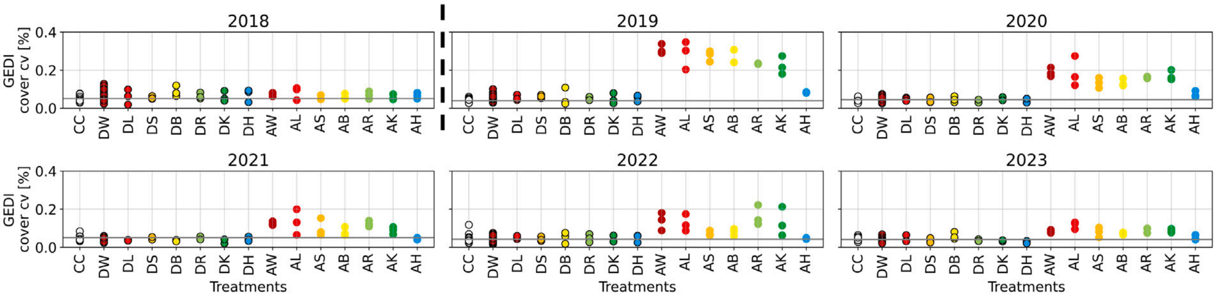
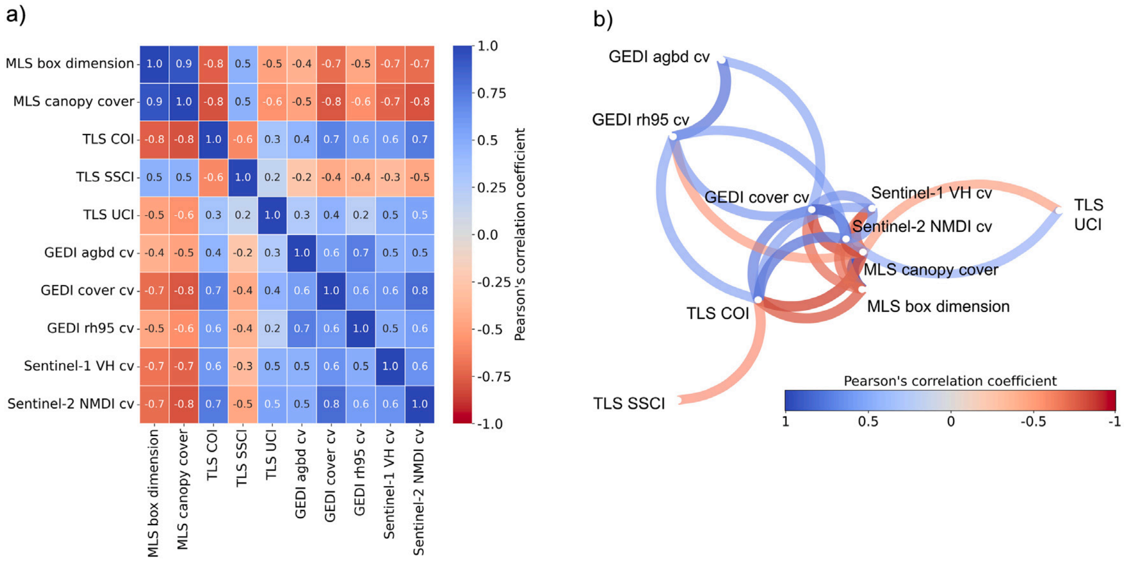


Fig. 4. GEDI total canopy cover coefficient of variation (cv) time-series at the patch-level from 2018 to 2023. A single point represents the structural complexity of a patch. The color-coding follows the schematic representation of BETA-FOR treatments in Fig. 1. The black contours of points for control and distributed treatments indicates the difference in structural complexity to aggregated treatments (no contours). The horizontal gray line in each plot shows the respective mean of control treatments (CC). The dashed vertical line represents the treatment implementation event in November to December 2018. Time-series of GEDI canopy height (rh95) and above-ground biomass density (agbd) can be found in the supplementary material C.



	MLS box dimension	MLS canopy cover	TLS COI	TLS SSCI	TLS UCI	GEDI agbd cv	GEDI cover cv	GEDI rh95 cv	Sentinel-1 VH cv	Sentinel-2 NMDI cv
MLS box dimension	1.0	0.9	-0.8	0.5	-0.5	-0.4	-0.7	-0.5	-0.7	-0.7
MLS canopy cover	0.9	1.0	-0.8	0.5	-0.6	-0.5	-0.8	-0.6	-0.7	-0.8
TLS COI	-0.8	-0.8	1.0	-0.6	0.3	0.4	0.7	0.6	0.6	0.7
TLS SSCI	0.5	0.5	-0.6	1.0	0.2	-0.2	-0.4	-0.4	-0.3	-0.5
TLS UCI	-0.5	-0.6	0.3	0.2	1.0	0.3	0.4	0.2	0.5	0.5
GEDI agbd cv	-0.4	-0.5	0.4	-0.2	0.3	1.0	0.6	0.7	0.5	0.5
GEDI cover cv	-0.7	-0.8	0.7	-0.4	0.4	0.6	1.0	0.6	0.6	0.8
GEDI rh95 cv	-0.5	-0.6	0.6	-0.4	0.2	0.7	0.6	1.0	0.5	0.6
Sentinel-1 VH cv	-0.7	-0.7	0.6	-0.3	0.5	0.5	0.6	0.5	1.0	0.6
Sentinel-2 NMDI cv	-0.7	-0.8	0.7	-0.5	0.5	0.5	0.8	0.6	0.6	1.0

Fig. 5. Correlation matrix (a) and correlation network (b) indicating the relationships among cross-scale metrics of forest structural complexity. For the correlation network, only metrics with an absolute correlation coefficient greater than 0.5 are considered.

Most strong correlations exist among the following metrics (core network group): MLS (box dimension, canopy cover), TLS (COI), Sentinel-1 VH cv, Sentinel-2 NMDI cv, GEDI cover. TLS SSCI, and UCI, as well as GEDI agbd cv, and rh95 cv, possess few correlations to the core network group, and no moderate to strong correlations among each other (except for GEDI agbd cv and GEDI rh95 cv).

3.3. Multivariate comparison of BETA-FOR treatment groups

In contrast to previous analyses for individual BETA-FOR patches (“3.1. Spaceborne Time-Series”, “3.2. Correlation Analysis”), a multivariate comparison of forest structural complexity metrics was conducted at the BETA-FOR treatment group-level (control, distributed, aggregated treatments) in order to assess the potential of various metrics to delineate different treatment groups. The bi-annual comparison (2019, i.e. first summer after treatment implementation, compared to 2023) of spaceborne-based metrics of forest structural complexity reveals varying patterns of structural complexity across treatment groups. In 2019, all metrics indicate increased structural complexity for aggregated treatments (mean values of 0.4 to 0.5 for all metrics) with no overlap (mean or standard deviation) to control and distributed treatments (Fig. 6(a)). Both control and distributed treatments indicate low structural complexity (mean values lower equal than 0.1 for all metrics) with nearly identical mean and standard deviation values. The analysis for 2023 shows reduced structural complexity for aggregated treatments compared to 2019, indicated by overlapping standard deviation ranges (Fig. 6(b)). According to mean values of structural complexity, aggregated treatments still possess increased structural complexity compared to control and distributed treatments. Furthermore, the different spaceborne metrics delineate aggregated treatments less distinctly: Sentinel-1 VH cv, Sentinel-2 NMDI cv, and GEDI cover cv demonstrate larger mean differences of aggregated to control and distributed treatments, in contrast to GEDI agbd cv, and GEDI rh95 cv.

Fig. 7 depicts a multivariate comparison of treatment groups with the integration of all metrics for 2023. All metrics from different remote sensing platforms and sensors delineate aggregated treatments from control and distributed treatments according to mean values. Nevertheless, MLS box dimension and canopy cover, Sentinel-2 NMDI cv, and GEDI cover cv do not possess any overlap (standard deviation) between aggregated treatments and the other two treatment groups, thus indicating a clear separation of aggregated treatments.

3.4. Unsupervised clustering analysis

Unsupervised K-Means clustering analysis was employed to assess the clustering of MLS, TLS, and spaceborne metrics at the patch-level. We tested the degree to which structural complexity metrics can delineate individual patches clustered according to their treatment groups (control, distributed, aggregated treatments). Clustering was

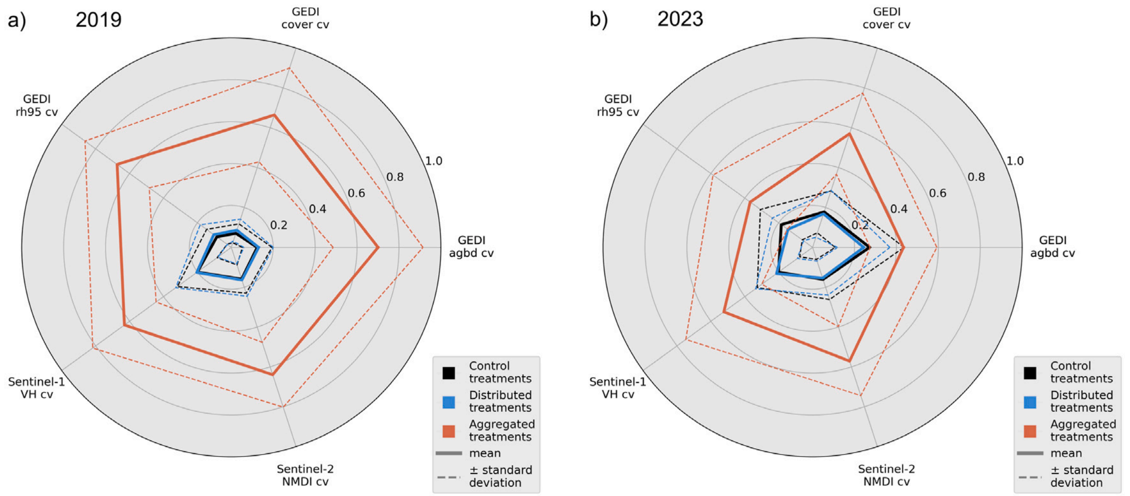


Fig. 6. Spaceborne metrics of structural complexity for 2019 (a) and 2023 (b) as multivariate comparison to assess differences in structural complexity among treatment groups. For consistent comparison across metrics, we applied a standardized scaling of all metrics to [0,1] — with values close to 0 indicating low structural complexity and values close to 1 indicating high structural complexity.

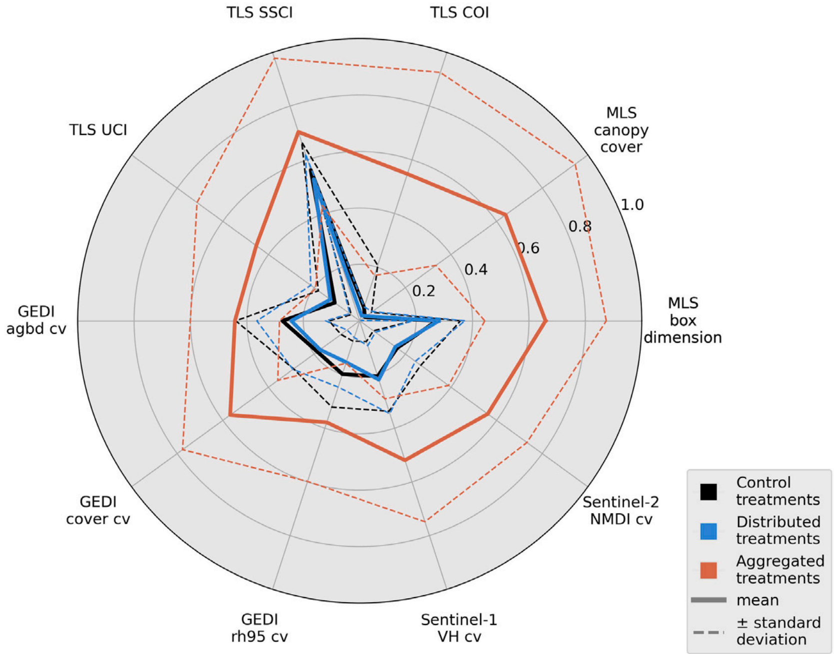


Fig. 7. All metrics of structural complexity (2023) as multivariate comparison to assess differences in structural complexity among treatment groups. For consistent comparison across metrics, we applied a standardized scaling of all metrics to [0,1] — with values close to 0 indicating low structural complexity and values close to 1 indicating high structural complexity.

conducted per platform ("3.4.1. Spaceborne Indicators", supplementary material E), and across platforms ("3.4.2. All Indicators"). The clustering output is visualized as stacked bar charts (frequency of clusters per treatment group) and scatter plots (selection of two metrics for visualization) color-coded by clusters and marker-coded by BETA-FOR treatment groups.

3.4.1. Spaceborne indicators

Clustering input data includes all spaceborne metrics (Table 1). Since the spaceborne data is available for multiple years, the clustering analysis was first conducted based on 2019 data to assess structural complexity immediately following treatment implementation. Fig. 8(a) demonstrates the frequency of clusters among BETA-FOR treatment groups: most aggregated treatments (85 %) are classified correctly in a single cluster (cluster 2). Only the aggregated treatments with habitat trees (AH) are incorrectly assigned as cluster 0 (Fig. 8(b)). Control and distributed treatments present confused cluster assignments, i.e. no accurate delineation of the two treatment groups. In comparison, the clustering analysis based on 2023 data shows a decline in the frequency of correct cluster assignments for aggregated treatments (60 %, Fig. 8(c)). False cluster assignments of aggregated treatments only occur for aggregated treatments with standing deadwood structures (aggregated snags, AS; aggregated downed deadwood and snags, AB; AH; Fig. 8(d)). Control and distributed treatments for 2023 data also exhibit confused cluster assignments.

3.4.2. All indicators (across-platforms)

The clustering analysis across-platforms integrates all calculated metrics of structural complexity based on MLS, TLS, and spaceborne

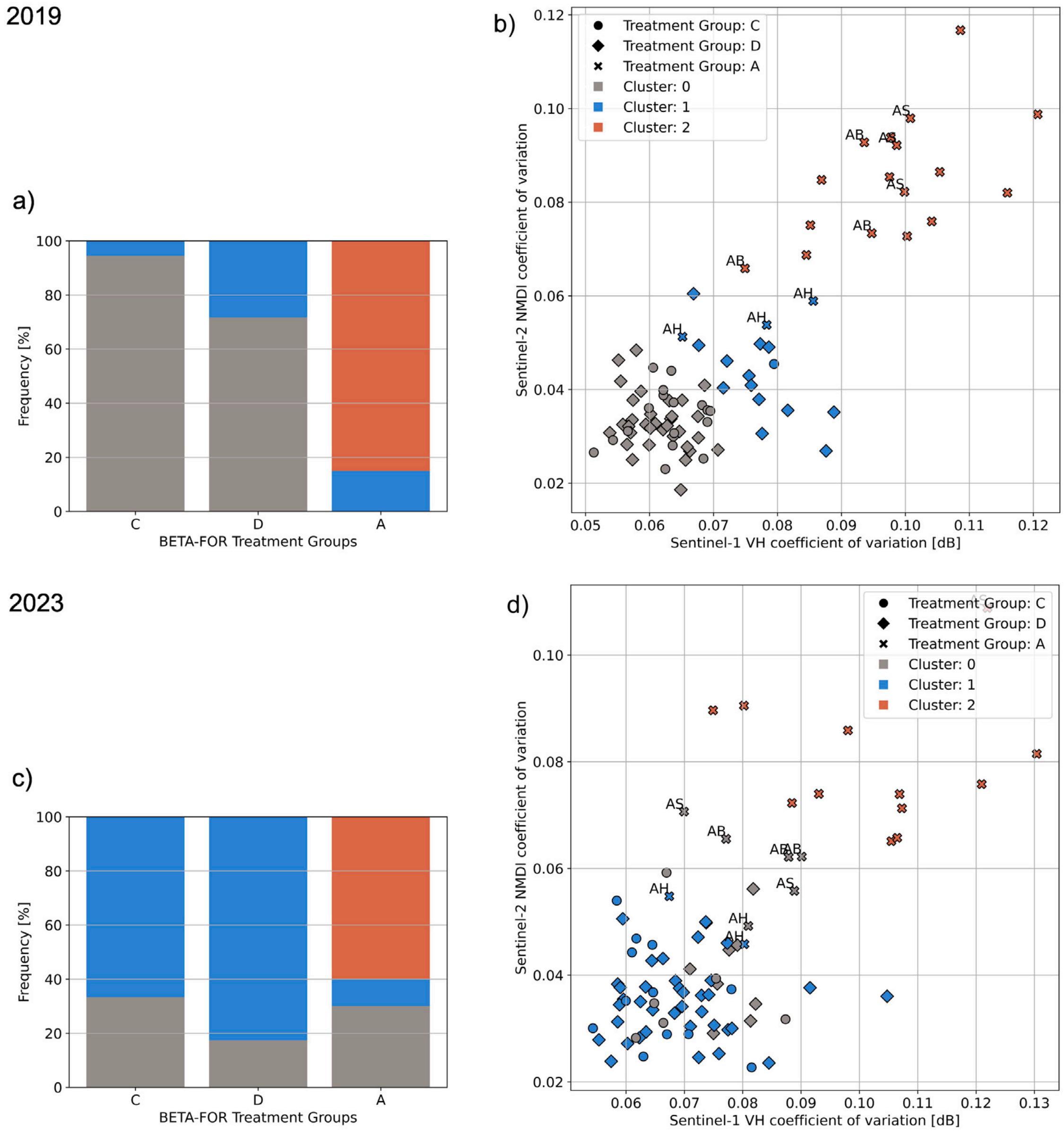


Fig. 8. Clustering results based on all spaceborne metrics for 2019 (a, b) and 2023 (c, d). The scattering follows the same pattern when other metrics are selected. The colors for individual clusters in the stacked bar charts are identical to the colors of clusters used in the scatter plot. C = control, D = distributed, and A = aggregated treatments. For the aggregated treatments with standing deadwood structures (AS, AB, AH, please see Fig. 1 for abbreviations), the treatment labels are shown since those treatments are not necessarily assigned to the cluster of aggregated treatments (cluster 2).

remote sensing data for 2023. The clustering results regarding the frequency of clusters per individual treatment group indicates a slight increase of correctly assigned aggregated treatments to a single cluster (65 %, Fig. 9(a)), compared to the clustering analysis for 2023 solely considering spaceborne metrics (Fig. 8(c)). Similar to the 2023 clustering analysis, solely based on spaceborne data, false cluster assignments of aggregated treatments only occur for treatments with standing deadwood structures (AS, AB, AH) when integrating across-platform metrics of structural complexity (Fig. 9(b)). Again, control and distributed treatments are classified to similar proportions of cluster 0 and 1, i.e. there is no clear delineation of the two treatment groups.

4. Discussion

4.1. Assessment of intra- and inter-platform correlations between MLS, TLS, and spaceborne metrics

The BETA-FOR patch network of experimental silvicultural treatments offers great potential for an assessment of forest enhanced structural complexity (ESC) under controlled conditions of standardized deadwood structures and light conditions (Mueller et al., 2022a,b). The combination of observations from sub-canopy (MLS, TLS) and above-canopy (Sentinel-1, Sentinel-2, GEDI) remote sensing enables the cross-validation of relationships from different platforms and among a

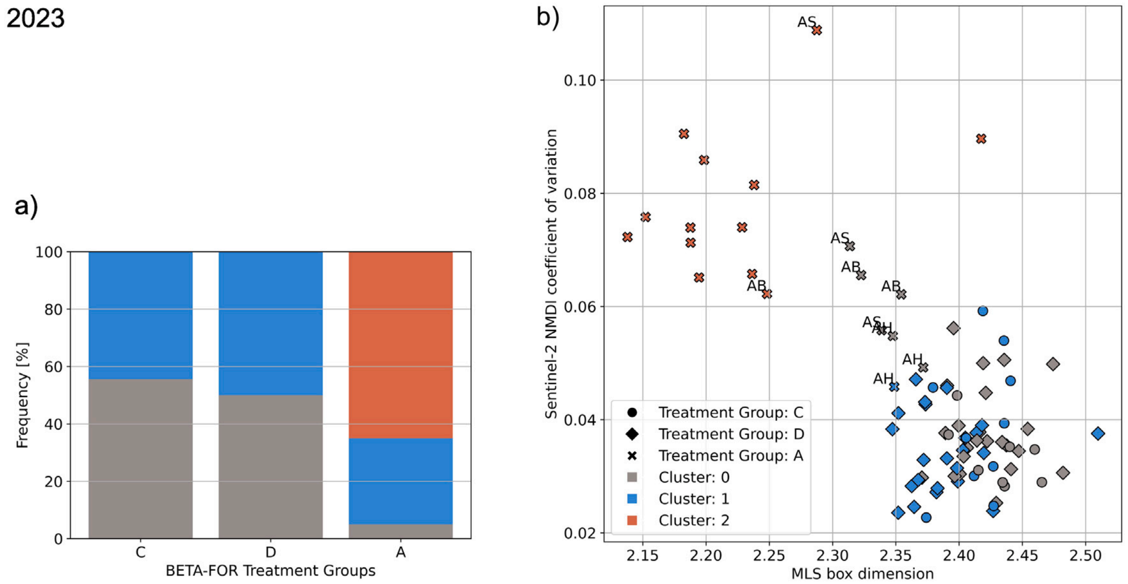


Fig. 9. Clustering results based on all calculated metrics of structural complexity for 2023. The scattering follows the same pattern when other metrics are selected. The colors for individual clusters of the stacked bar charts are identical to the colors of clusters used in the scatter plot. C = control, D = distributed, and A = aggregated treatments. For the aggregated treatments with standing deadwood structures (AS, AB, AH, please see Fig. 1 for abbreviations), the treatment labels are shown since those treatments are not necessarily assigned to the cluster of aggregated treatments (cluster 2). Since cluster 0 and 1 hold similar shares of control and distributed treatments, they cannot be clearly assigned to either control or distributed treatments.

range of metrics characterizing different structural attributes (Table 1, "Metrics classification"). In addition, the integration of complementary measurements of structural complexity based on radar (Sentinel-1), multispectral (Sentinel-2), and lidar (GEDI) supports cross-sensor comparisons (Atkins et al., 2023a,b; LaRue et al., 2020). From spaceborne time-series, similar forest structural complexity profiles in control, distributed, and aggregated patches before treatment implementation events confirm the agreement of different remote sensing sensors for forest structural complexity analyses (Figs. 2, 3, 4).

The identification of moderate to strong inter-platform correlations (r >= 0.6) among Sentinel-1 VH cv, Sentinel-2 NMDI cv, and GEDI cover cv is in agreement with our research hypothesis (1). Therefore, specific metrics of Sentinel-1, Sentinel-2, and GEDI have the potential to bridge scales of in-situ measures of structural complexity (MLS box dimension, MLS canopy cover, TLS COI). It is important to note that the spaceborne metrics assess structural heterogeneity and can serve as proxies for in-situ metrics on structural complexity (e.g. MLS box dimension) and canopy cover or the inverse metric of canopy openness (e.g. MLS canopy cover, TLS COI). Therefore, across-platform relationships of the aforementioned metrics support our research hypothesis (1) that relationships among complementary attributes of structural complexity (e.g. canopy cover, structural heterogeneity, structural complexity) are present at both intra- (e.g. MLS box dimension, MLS canopy cover, r = 0.9), and inter-platform perspectives (e.g. MLS box dimension, GEDI cover cv, r = −0.7). In addition, we found strong correlations (|r| >= 0.7) among across-platform metrics of canopy cover (MLS canopy cover, TLS COI, GEDI cover cv). In our analyses, canopy cover reaches its natural limit of 100 % in several of our observations, while other metrics can still assume a broader range of values in forests with 100 % canopy cover (please see Supplementary Material A, Fig. 2). Therefore, the correlations found between canopy cover (e.g. MLS canopy cover) and other metrics of structural complexity are not transferable to sets of forest stands that all hold (nearly or exactly) canopy cover values of 100 % – the correlations might only hold if a broader range of canopy cover is included. Negative correlations between MLS metrics (box dimension, canopy cover) and spaceborne metrics (GEDI agbd cv, GEDI total canopy cover cv, GEDI canopy height cv, Sentinel-2 NMDI cv) were found because the two MLS metrics are inverse to the aforementioned spaceborne metrics, i.e. the lower MLS box dimension and canopy cover, the higher the structural complexity (e.g. aggregated treatments, supplementary material A: Figure 1 and 2). GEDI agbd cv, GEDI total canopy cover cv, GEDI canopy height cv, and Sentinel-2 NMDI cv express increased structural complexity as higher values (please see Fig. 2, Fig. 3, supplementary material C: Figure 1 and 2).

Our research hypothesis (2) was confirmed, since metrics of structural complexity based on MLS, TLS, and spaceborne remote sensing identified major increases in structural complexity following treatment (aggregated treatments, Fig. 7). ESC in distributed treatments through deadwood manipulation and selective logging could neither be identified by close-range (MLS, TLS), nor spaceborne remote sensing (Sentinel-1, Sentinel-2, GEDI). This finding is supported by a recent study from Kacic et al. (2024) testing the identification of treatment implementations through 84 Sentinel-1 metrics and 903 Sentinel-2 metrics based on a comprehensive catalogue of spectral indices (Montero et al., 2023). More precisely, both Sentinel-1 and Sentinel-2 have the potential to accurately detect various aggregated treatment implementations when specific spectral indices and spatial statistics are selected (e.g. Sentinel-1 VH cv, Sentinel-2 NMDI cv). Structural manipulation in distributed treatments, primarily via selective thinning, were not detected based on Sentinel-1 and Sentinel-2 data (at 10 m spatial resolution). The change in canopy cover is likely to be measured as mixed pixel signal resulting from overlapping tree crowns and pixels not being aligned with the selectively removed trees (Kacic et al., 2024). Presumably, the dynamic responses of understorey vegetation and the crowns of the remaining trees are the reason for the lack of significant pre- and post-intervention differences in distributed treatments based on close-range and spaceborne remote sensing.

4.2. Sensitivity of MLS, TLS, and spaceborne metrics towards standing deadwood structures in aggregated treatments

Based on unsupervised clustering, metrics from different platforms and sensors of structural complexity are sensitive to the structural characteristics of standing deadwood (Figs. 8, 9). Aggregated treatments with standing deadwood structures are more likely not to be assigned to the cluster of aggregated treatments. This finding suggests that there is a difference in the structural signal measured in aggregated treatments without standing deadwood structures (AR, AW, AL), and aggregated treatments with snags, and habitat trees (AS, AB, AH). Therefore, the Sentinel-1 and -2 metrics identifying the treatment implementation event in aggregated treatments (Kacic et al., 2024) might be sensitive to the change in canopy cover, as well as the presence of standing deadwood. In addition, we found a sensitivity to the time interval of the disturbance event, due to the fact that in the clustering analysis for 2019, 85 % of aggregated treatments were assigned to a single cluster (only aggregated treatments with habitat trees were incorrectly assigned). In 2023, the frequency of aggregated treatments being assigned to a single cluster amounts to 60 %, i.e. 40 % of false cluster assignments of aggregated treatments with standing deadwood. Therefore, the clustering of aggregated treatments depends on the time interval of the treatment event, as well as the presence of standing deadwood structures (incomplete confirmation of hypothesis (3)).

4.3. *Understanding the physical mechanisms of remotely sensed forest structural complexity assessment*

Our findings suggest that LiDAR measurements from sub-canopy and top-of-canopy are sensitive to similar structural characteristics (e.g. leaf area, branch and stem volume): Optical active spaceborne LiDAR (GEDI) coverage estimates are highly correlated to MLS canopy cover and TLS Canopy Openness Index. In a previous study, both Sentinel-1 (cross-polarized radar scattering) and Sentinel-2 (spectral reflectance information with a sensitivity to drought conditions) characterize the structural changes from closed canopies to open canopies with various deadwood structures (no deadwood present, standing deadwood, habitat trees) (Kacic et al., 2024). Sentinel-2 NMDI cv is highly correlated with metrics related to canopy surface structure (MLS canopy cover, TLS Canopy Openness Index), thus suggesting the applications of Sentinel-2 (optical passive sensor) for surface measurements. Sentinel-1 (active radar) penetrates the forest canopy to some extent, since high correlations are not only found for MLS canopy cover and TLS Canopy Openness Index, but also for MLS box dimension which holds information on 3D structure. The correlation network (Fig. 5b) highlights that there are unique TLS metrics in terms of that they are uncorrelated with other metrics (UCI and SSCI) which means that these below-canopy features cannot be properly estimated from space (e.g. through GEDI measurements of canopy height, total canopy cover, above-ground biomass density). Another study integrated Sentinel-1 and Sentinel-2 time-series composites to model GEDI-derived forest structural attributes (e.g. canopy height) based on relationships of radar and multispectral to LiDAR measurements (Kacic et al., 2023). The canopy height accuracy of machine learning models amounts to Mean Absolute Errors (MAE) of 4.4 m, thus confirming the general potential of sensor fusion for forest structure modeling. Future research applications integrating remote sensing data in order to assess forest conditions should consider different platforms and sensors to strengthen the understanding of close-range to spaceborne sensing. The agreement among different metrics for being sensitive to specific structural conditions could provide the basis for a catalogue of remotely sensed metrics with good alignment for the derivation of forest structural conditions from both in-situ and spaceborne perspectives. For multi-annual time-series analyses and large-scale studies, the integration of spaceborne radar is of high relevance due to its insensitivity towards atmospheric conditions compared to optical sensors. Therefore, the combined analysis of e.g. Sentinel-1 and Sentinel-2 should be best practice in spaceborne forest research for cross-validation of temporal and spectral characteristics.

4.4. *Standing deadwood and its relationship to biodiversity*

Further research is needed in the context of delineating standing deadwood structures based on remote sensing across forest types and over time, since standing deadwood strongly promotes multifunctionality (van Der Plas et al., 2016), biodiversity (Hendel et al., 2023; Kortmann et al., 2018; Seibold et al., 2016a,b, 2019), and resilience (Ma et al., 2023; Staab et al., 2023; Thorn et al., 2018). Current remote sensing research on standing deadwood in Central European forests identified the general potential of Sentinel-2 for the early detection of bark beetle infestation (Abdullah et al., 2019; Bárta et al., 2021; Jamali et al., 2023; König et al., 2023), which is often followed by canopy cover loss (Thonfeld et al., 2022). In addition, potential standing deadwood areas in the German Harz forest could be detected based on annual mapping of forest structure for Germany. Composite stacks (Red-Green-Blue images) of modeled GEDI-derived attributes of forest structure (canopy height, total canopy cover, and above-ground biomass density) based on spatio-temporal composites of Sentinel-1 and Sentinel-2 data characterize potential standing deadwood areas as relatively large canopy height and low total canopy cover (Kacic et al., 2023).

Cross-scale metrics on forest structural complexity are valuable indicators for forest management in the context of biodiversity assessment (Heidrich et al., 2020, 2023; Skidmore et al., 2021). Recent studies on Central European forests report declining insect abundance and biomass (Seibold et al., 2019; Staab et al., 2023). The effect of forest management on biodiversity has been identified as important factor (Chaudhary et al., 2016; Paillet et al., 2010; Zeller et al., 2021, 2023), since management promoting late successional forest structures (e.g. retention forestry, continuous cover forestry, natural regeneration) positively influences insect habitats (Staab et al., 2023). Previous studies on habitat structure characterization of multi-taxa have demonstrated the potential of ALS and Sentinel-1 metrics (Bae et al., 2019; Heidrich et al., 2020, 2023). The present study considers various metrics across different platforms and sensors to estimate complementary attributes of forest structure that have proven their sensitivity to canopy and deadwood structures, i.e. the two major structural gradients among BETA-FOR patches, thus being valuable indicators of management for structural complexity (Messier et al., 2021; Müller et al., 2018b).

4.5. *Outlook on interdisciplinary research in the context of enhanced structural complexity in forests*

The need for in-depth integration of remote sensing in ecological research was recently emphasized by Burrascano et al. (2023) and Cavender-Bares et al. (2022), in order to meet global biodiversity goals (Díaz et al., 2020; Nabuurs et al., 2022). Since the present study identified various intra- and inter-scale relationships of forest structural complexity indicators, further joint research of ecologists, biologists, and remote sensing scientists is essential to holistically link forest structure, ecosystem functioning, and biodiversity from local to global levels (Jetz et al., 2016). Guiding forest management based on interdisciplinary research on ESC (comprising α-, β-, and γ-diversity) is the primary goal of the BETA-FOR project (Mueller et al., 2022a). A wide range of standardized measurements have been conducted: assessing forest structure through in-situ and spaceborne observations, measuring volatilomes, surveying microbial diversity in soils and various deadwood structures, quantifying decomposition rates, capturing plant-animal interactions (pollination, parasitism, seed dispersal), identifying understory plant assemblages, and the analysis of multifunctionality and higher trophic level diversity (Mueller et al., 2022b). Therefore, various research gaps are actively being addressed, such as ESC through experimental silvicultural manipulations (Messier et al., 2021), correlation of in-situ to spaceborne observations (Burrascano et al., 2023; Cavender-Bares et al., 2022), the relationship of forest structure and microclimate (Großmann et al., 2023; Zellweger et al., 2019, 2020), varying deadwood amount, type, and structures (Sandström et al., 2019), altered plant species richness due to different light regimes (Dormann et al., 2020), and the response of multi-trophic groups to structural complexity (Penone et al., 2018).

The BETA-FOR treatments aim to mimic old-growth structures (or to accelerate their development) through experimental silvicultural manipulation, i.e. increased structural complexity through diverse light conditions and varying amount, and type of deadwood. In this context, research on the agreement of structures, as well as ecosystem functioning, and biodiversity of BETA-FOR patches, and natural old-growth forests could further validate the experimental treatment design (Franklin and Van Pelt, 2004; Martin and Valeria, 2022). Furthermore, changes in beta-diversity among BETA-FOR patches are valuable references for the comparative analysis to natural disturbances and their impact on turnover in structures, taxa, and functioning (Hilmers et al., 2018; Myers et al., 2015). Since the BETA-FOR patch network is limited to German broad-leaved forests, assessing the influence of experimental silvicultural treatments in broad-leaved forests of other countries and continents would be a valuable step to further transfer the findings from national to continental, and global levels.

5. Conclusion

Diverse deadwood structures (no deadwood present, stumps remaining, downed deadwood, standing deadwood, habitat trees) and varying light conditions (distributed and aggregated cuttings) have been implemented in an intensively managed German broad-leaved forest as part of the BETA-FOR program. This study analyzes enhanced forest structural complexity through experimental silvicultural treatments based on various remotely sensed data (mobile and terrestrial laser scanning, satellite radar, satellite multispectral, spaceborne lidar). In the following we present three major conclusions that we draw from our analyses:

(1) We identified strong intra- and inter-platform relationships among metrics of forest structural complexity. The comparative analyses of mobile laser scanning, terrestrial laser scanning, Sentinel-1, Sentinel-2, and GEDI data demonstrates the potential of spaceborne metrics to upscale in-situ measurements of structural complexity.

(2) In-situ and spaceborne metrics of forest structural complexity delineated major increases in structural complexity through aggregated treatments (gap felling). No difference in structural complexity between control and distributed treatments was observed from either in-situ or spaceborne metrics.

(3) Metrics of forest structural complexity from different platforms and sensors were sensitive to the structural characteristics of standing deadwood in gaps (aggregated treatments). Further research is needed to assess the sensitivity of spaceborne metrics to standing deadwood over time and across forest types in order to improve the characterization of post-disturbance habitat structures.

In conclusion, in-situ and spaceborne indicators of structural complexity sufficiently demonstrated their potential for monitoring adaptive silvicultural management due to their sensitivity to enhanced structural complexity. Based on our findings, we suggest a deeper integration of spaceborne remote sensing into operational forest structure monitoring, e.g. to extrapolate in-situ measurements (close-range remote sensing estimates and biodiversity sampling) over space and time for continuous coverage, to assess potential resilience of forests based on structural properties, and to monitor management efforts targeting enhanced structural complexity.

CRediT authorship contribution statement

Patrick Kacic: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ursula Gessner:** Writing – review & editing, Supervision. **Christopher R. Hakkenberg:** Writing – review & editing. **Stefanie Holzwarth:** Writing – review & editing. **Jörg Müller:** Writing – review & editing, Funding acquisition, Conceptualization. **Kerstin Pierick:** Writing – review & editing, Data curation. **Dominik Seidel:** Writing – review & editing, Funding acquisition, Data curation. **Frank Thonfeld:** Writing – review & editing. **Michele Torresani:** Writing – review & editing. **Claudia Kuenzer:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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 material related to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113085.

Data availability

Data will be made available on request.

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