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Identification of even- and uneven-aged forest stand structures using freely available national airborne laser scanning data on National Forest Inventory plots in spruce-beech-fir dominated regions

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Even-aged forests are still predominant across Europe. However, due to the higher resilience and resistance of uneven-aged forests to disturbances and climate change, their proportion is expected to increase both in Europe and globally. The primary objective of this study is to demonstrate the feasibility of distinguishing between uneven- and even-aged forest stand structures on National Forest Inventory (NFI) permanent sample plots solely based on freely available, national airborne low-resolution laser scanning data, without the use of field-based estimates or measurements. Forest structure was described and classified based on canopy closure, dominant height, and canopy height diversity derived from the canopy height model (CHM) and voxel-based metrics calculated from the point cloud. Comparable results were obtained using both approaches for assessing forest structural diversity: canopy height diversity derived from the canopy height model (CHD_{CHM}) and from voxel-based metrics (CHD_V). However, differences in vertical diversity between uneven- and even-aged stands were more pronounced when using CHM-based metrics. Therefore, we conclude that in areas with low-density laser scanning data, CHM analysis represents a more suitable method for evaluating the vertical heterogeneity of forest stand structures. The CHD_{CHM} values were estimated at 1.71 for uneven-aged forests, with values of 1.24 and 1.54 observed in mature even-aged forests. In comparison, CHD_V values were 2.50 for uneven-aged forests, while mature even-aged forests showed values of 2.18 and 2.24.

KEYWORDS
vertical heterogeneity, National Forest Inventory, canopy height model, voxels, uneven-aged and even-aged forests

1 Introduction

Even-aged forests continue to dominate across Europe, accounting for approximately 75% of forested areas (ForestEurope, 2020). However, due to the greater resilience and resistance of uneven-aged forests to disturbances and climate change (Lafond et al., 2014; O'Hara and Ramage, 2013) their proportion is expected to increase both in Europe and globally. Thus, interest in the establishment and management of uneven-aged forests has already grown in recent years (Dănescu et al., 2016). Structural heterogeneity of the forest is primarily the result of frequent silvicultural interventions over space and time, or from small-scale natural disturbances (Kukunda et al., 2019). Forest stand structure encompasses vertical elements (e.g., number of canopy layers), horizontal elements (e.g., spatial distribution of trees, gaps), and species (Maltamo et al., 2005).

Clear-cutting is legally prohibited in Slovenia under national forest management legislation (ZG, 1993). Forest management in the Republic of Slovenia is guided by the principles of sustainability, close-to-nature silviculture, multifunctionality, and forest management planning in order to ensure the long-term conservation of forests and their ecosystem services (ReNGP, 2007). The structural heterogeneity of Slovenian forests is primarily the result of small-scale forest management practices (ReNGP, 2007). Frequent, small-scale interventions in forests lead to the development of structurally heterogeneous stand structures or patches as well as mosaic-like stand structures with varying degrees of structural heterogeneity at the fine scale. Uneven-aged forests prevail in Slovenia (Bončina et al., 2002), with the most representative forest types occurring in mixed spruce-fir-beech forests on carbonate bedrock in the Dinaric and the Alpine eco-regions and mixed spruce-fir-beech forests on silicate bedrock in the Pohorje eco-region (Klopčič and Bončina, 2012).

At the national level, field data were collected in Slovenia until 2018 as part of the Monitoring of Forests and Forest Ecosystems (MFFE) program (Skudnik et al., 2021a; Skudnik et al., 2021b) which was implemented on permanent sample plots in a systematic 4 × 4 km grid. The plots were surveyed in 2000, 2007, 2012, 2018, and 2024. In 2020, the MFFE inventory was upgraded and converted into the National Forest Inventory (NFI). The NFI is based on an unaligned 2 × 2 km grid, with measurements being repeated on the same plots every 5 years. The NFI is designed as a panel inventory system (Skudnik et al., 2023), where the entire grid is divided into five panels and one panel is measured in each year. The former MFFE plots have been incorporated as the fifth panel in the NFI. In this way, the NFI collects data on the condition and dynamics of Slovenian forests annually, based on a representative sample with an effective spatial density of approximately 4 × 4 km. In total, approximately 750 plots are surveyed each year, and the complete NFI covers approximately 3,750 plots across the entire country (Pintar et al., 2024).

In the Slovenian NFI plots, the vertical forest stand structure is currently estimated based on expert judgment (Skudnik et al., 2022a). Although field crews undergo calibration of estimation procedures before each annual inventory, inter-observer variability can still lead to discrepancies. Therefore, the aim of this study is to investigate the potential of estimating vertical forest structure using freely available airborne low-resolution laser scanning data, which could subsequently be verified and complemented during field surveys. Within the NFI protocol (Skudnik et al., 2022a), tree heights are only measured for a subsample of trees in each plot, which means that even the available field measurements do not capture the entire vertical structure of the stand. In addition, remote sensing approaches—particularly those based on laser scanning—enable more accurate and efficient estimates of tree heights under optimal conditions compared to traditional field-based methods such as optical triangulation (Ganz et al., 2019).

The main objective of this study is to demonstrate the feasibility of distinguishing between uneven- and even-aged forest stand structures on NFI plots solely based on freely available, national airborne low-resolution laser scanning data, without the use of field-based estimates or measurements.

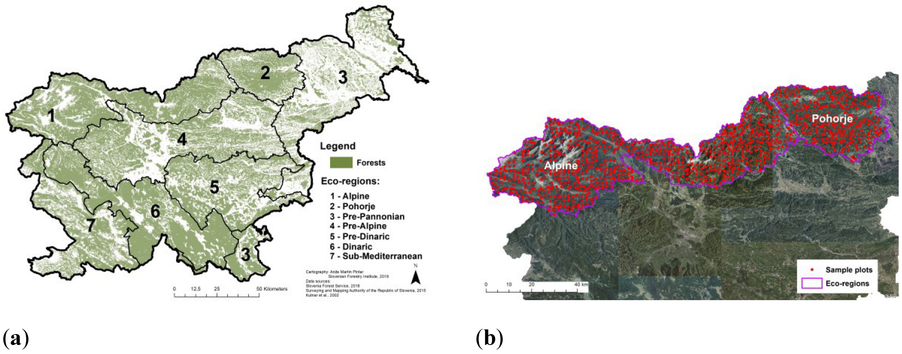
2 Materials and methods

2.1 Study area

Slovenia lies at the intersection of Central and Southeastern Europe, forming a transitional geographic and ecological zone. The country is divided into seven ecological regions (Figure 1a), delineated based on key natural geographical factors, including vegetation, geology, soil types, and climatic conditions. These regions align with the phytogeographical classification of Slovenia. The study area represents the Alpine and Pohorje ecological regions (Figure 1b). The total forest area in Slovenia is 1,177,165 ha (SFS, 2025), of which 291,300 ha are located in the Alpine and Pohorje ecological regions.

In the Alpine and Pohorje ecological regions, Norway spruce (*Picea abies*) is the predominant tree species in the growing stock (49 and 51%), European beech (Fagus sylvatica) represents 27% in the Alpine and 13% in the Pohorje region while silver fir (*Abies alba*) accounts for 4 and 19%, respectively (Pintar et al., 2024). The analysis was carried out using permanent sample plots from all five panels of the NFI (Pintar et al., 2024; Skudnik and Hladnik, 2018).

The three most prevalent tree species in the Alpine and Pohorje ecological regions are all native in the area. Historically, Norway spruce has been more intensively promoted in these regions compared to European beech, reflecting broader historical silvicultural practices in Slovenian forests, largely due to the high commercial value of spruce timber (Kutnar et al., 2021). These three species also dominate forest composition at the national level (Pintar et al., 2024). A total of 951 permanent sample plots were analyzed, comprising 705 plots in the Alpine region and 246 in the Pohorje region. Both regions were selected for the analysis due to their similar tree species composition (Pintar et al., 2024), comparable stand structural characteristics (Kušar and Kovač, 2024), and the presence of typical uneven-aged fir–spruce–beech forests growing on silicate and carbonate bedrock (Klopčič and Bončina, 2012). The natural geographic conditions in both regions are largely comparable, with the exception of differences in parent substrate (Kutnar et al., 2002). The study area encompasses the heterogeneous slopes of the Pohorje Mountains, the Karawanks, the Kamnik-Savinja Alps and the Julian Alps extending to the upper forest limit at approximately 2,000 m above sea level.



(a) (b)

FIGURE 1
The entire territory of Slovenia with the forest mask and ecological regions marked **(a)**, and the Alpine and Pohorje ecological regions with marked National Forest Inventory plots **(b)**.

2.2 Data preparation

Freely available airborne laser scanning (ALS) data from the first nationwide laser scanning campaign in Slovenia, which was carried out in 2014 and 2015 as part of the Laser Scanning of Slovenia (LSS) project, were used in this study (Triglav Čekada and Bric, 2015). The first laser scanning of Slovenia was carried out with the Eurocopter EC 120B helicopter at flight height from 1,200 to 1,400 m above the ground. The lidar system consisted of a RIEGL LMS-Q780 laser scanner with a pulse frequency of 400 kHz and a positioning and orientation system [differential GNSS Novatel OEMV-3, INS IGI Aerocontrol Mark II rotation measurement system (E 256 Hz)]. The mean acquisition density was 5 points per m^2, using a laser beam footprint 30 cm in diameter, with a horizontal positional accuracy of 30 cm and an ellipsoidal height accuracy of 15 cm (Pegan Žvokelj et al., 2015).

All ALS data analyses were performed on NFI plots in the Alpine and Pohorje ecological regions, each with an area of 600 m^2. Spatial analyses were performed in ArcMap 10.8 (ESRI, 2018). The raster map of voxel-based canopy height diversity (CHD_V) with a resolution of 10 m, as well as a canopy height model (CHM) with a resolution of 1 m, were previously generated by Kobler (2024) and Kobler (2015). From the ALS data, we derived variables that have been used in a similar way to typify stand structures based on vertical diversity (Pintar and Skudnik, 2024a; Pintar and Skudnik, 2025): dominant height, canopy closure and canopy height diversity using a canopy height diversity (CHD_{CHM}) and voxels (CHD_V). The procedures for calculating these variables are described in detail below.

In order to identify individual tree tops in the CHM, we applied a local maxima search using a circular moving window with a radius of 3 m. This radius was selected to approximate the average crown radius of dominant tree species in the study region, as reported by Pretzsch et al. (2015), ensuring that only one local maximum is detected per tree crown. The detected local maxima were then used to represent individual canopy trees and to construct a digital model of treetops. Dominant height was calculated using a standard method commonly employed in forest inventory studies, in which the height of the 100 tallest trees per hectare (Tarmu et al., 2020) serves as the dominant height reference. For each NFI plot (600 m^2), this corresponds to selecting the six tallest detected local maxima within the plot extent (Tarmu et al., 2020). The mean height of these selected treetops was used as the dominant tree height for the plot. On plots where fewer than six trees were detected (e.g., recently harvested stands), the dominant height was calculated as the mean height of all available detected treetops. In addition, the canopy closure was computed as the proportion of the plot area in the CHM with tree heights higher than 5 m (Pintar and Skudnik, 2024a; Pintar and Skudnik, 2025).

The CHM was classified into 5 m height classes, according to the FAO (2020). This classification scheme has already proven suitable for characterizing forest structure in the Pohorje region (Šprah, 2019; Pintar and Skudnik, 2024a; Pintar and Skudnik, 2025). The first class includes tree heights from 0 to 5 m and the last class tree heights above 40 m. For each permanent sample plot, the area covered by each height class and its relative proportion were calculated. These data were then used to calculate the canopy height diversity (CHD_{CHM}) using Equation (1). Comparable indices for assessing vertical forest structure have been previously proposed and applied in similar contexts (Stark et al., 2012; Palace et al., 2015; Hladnik et al., 2020; Hirschmugl et al., 2023; Pintar and Skudnik, 2024a; Pintar and Skudnik, 2025). The p_i value represents the proportion of the area of each height class to the total area of the permanent sample plot.

$$CHD_{CHM} = -\Sigma p_i \ln\left(p_i\right) \tag{1}$$

Kobler (2020) generated raster maps from the ALS point clouds that consider the relative frequencies of reflections along 5 m height classes (voxels). These voxel-based maps were subsequently used by Kobler (2024) to create voxel-based canopy height diversity raster [CHD_V, Equation (2)] covering the entire study area.

$$CHD_V = -\Sigma p_i \ln\left(p_i\right), \tag{2}$$

2.3 Statistical analysis

2.3.1 Classification of NFI permanent sample plots into stand structure types

The stand structures within the sample plots were classified using two separate K-means clustering analyses (Figure 2). In the first analysis, vertical structural diversity was assessed using

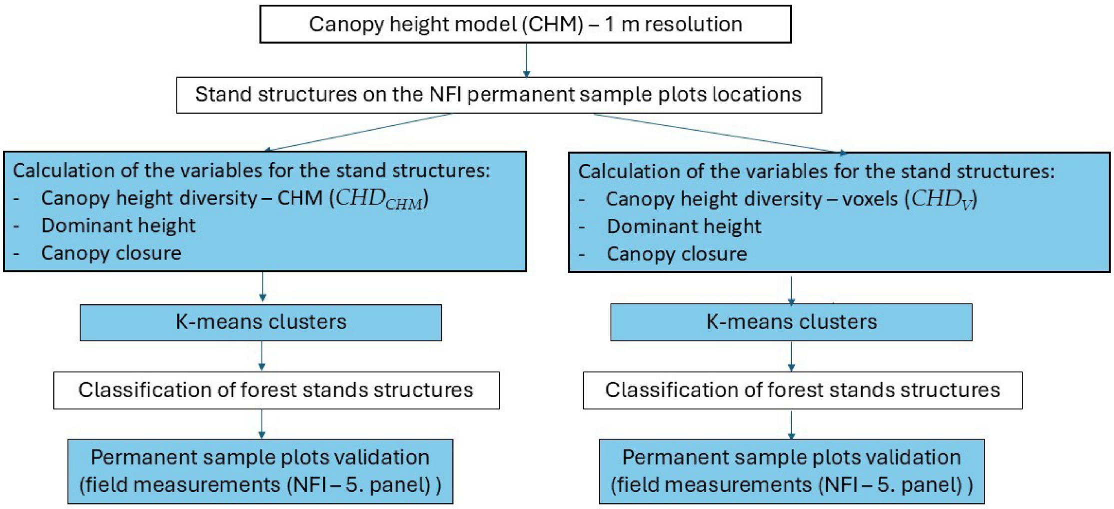


FIGURE 2
Workflow for the classification and validation of the stand structures.

CHD derived from the CHM, while in the second analysis, *CHD* was derived from voxel-based data. In both approaches, dominant height and canopy closure were considered as additional input variables. The optimal number of clusters was determined using the elbow method, which minimizes total within-cluster variance (UC, 2020). To validate the classification results, at least 20 individual stand structures from each cluster (in both analyses) were visually assessed on NFI plots using ALS CHM, cross-sections of the ALS point cloud, and orthophotos. This assessment served to confirm the structural characteristics of the clusters. The statistical analyses were performed using the R software environment (version 4.4.1) (R Core Team, 2025).

2.3.2 Validation of the classification by field measurements

The classification of stand structures was validated using field measurements from Panel 5 of the 2018 NFI data. This dataset was selected for validation due to its temporal proximity to the ALS survey and the previously demonstrated suitability of comparing 2014/2015 ALS data with NFI 2018 measurements (Skudnik et al., 2022b). A total of 179 sample plots were included in the validation. The center of each plot was georeferenced using a Leica GG04 plus GNSS receiver. The precise spatial alignment of the plots was achieved by matching the locations of canopy trees identified through field measurements with the corresponding tree positions visible on the CHM derived from ALS data. Each circular sample plot covered an area of 600 m^2, with a radius of 13.82 m. The positions of the trees were determined based on the distance from the center the plot and azimuth. All trees with a diameter at breast height (DBH) of 30 cm or more were recorded over the entire plot. In the inner subplot (200 m^2, radius 7.98 m), trees with a DBH of 10 cm or more were also recorded (Skudnik et al., 2022a). We analyzed potential differences between the classified stand structures using four variables: basal area, growing stock, number of trees and Shannon-Wiener index (*H'*). The first three variables were obtained directly from the NFI database (Pintar et al., 2024; Skudnik et al., 2023) while the Shannon–Wiener index was calculated using Equation 3. p_i represents the proportion of the basal area per hectare that comes from trees of a particular diameter class in relation to the total basal area per hectare on the plot.

$$H' = -\Sigma p_i \ln\left(p_i\right), \tag{3}$$

Since the assumption of normality of the distribution of the variables was not met, we used the non-parametric Kruskall-Wallis test for the test of statistical differences and Dunn's test for multiple comparisons and Holm's p-value correction for the posterior test.

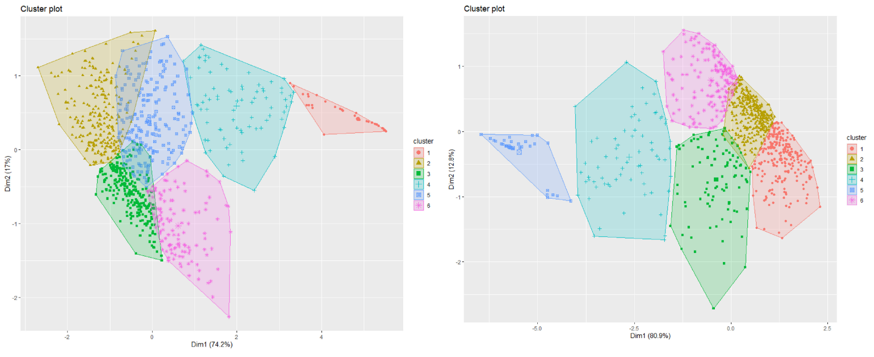
3 Results

3.1 Classification of NFI permanent sample plots into stand structure types

In the first analysis using CHM to assess canopy height diversity (CHD_{CHM}), Cluster 2 exhibited the highest CHD_{CHM} values, indicating the presence of the most vertically heterogeneous stand structures. Cluster 5 showed a slightly lower but still high value (Figures 3, 4 and Table 1). In addition, Cluster 2 also had a notably higher dominant height compared to Cluster 5. In contrast, Cluster 1 demonstrated the lowest values for both dominant height and CHD_{CHM} as well as canopy closure and is thus characterized as the most vertically homogeneous stand structures with low height—seedling stands.

Cluster 3 is characterized by relatively lower CHD_{CHM} values and high dominant height and canopy closure, indicating a more pronounced heterogeneity in the canopy of the stand. Clusters 4 and 6 both exhibit low CHD_{CHM} values and comparable dominant heights. However, they differ in canopy closure, with Cluster 4 showing markedly lower values.

In the second analysis, which employed voxel-based metrics to assess canopy height diversity, Cluster 1 exhibited the highest



(a) (b)

FIGURE 3
Classification of forest stand structures into clusters within the NFI plots. CHM was used **(a)** to estimate the *CHD* and voxels **(b)** were used to estimate the *CHD*.

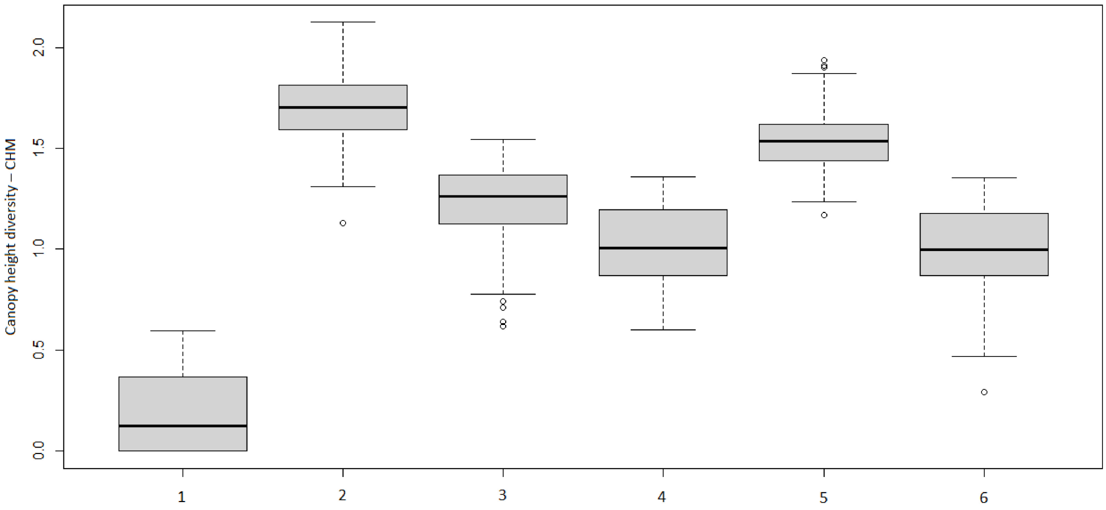


FIGURE 4
Boxplots for the CHD_{CHM} according to individual stand structure type clusters of the NFI plots.

TABLE 1 Number of plots, dominant height (h_{dom}), canopy closure and canopy height diversity (CHD_{CHM}) and associated standard deviations (SD) and coefficients of variation (CV) using CHM for each stand structure type cluster.

Cluster	Number of plots	h_{dom} (m)	SD_1 (m)	CV_1 (%)	Canopy closure	SD_2	CV_2 (%)	CHD_{CHM}	SD_3	CV_3 (%)
1	47	4.1	6.2	154.0	0.05	0.06	124.4	0.18	0.19	103.4
2	251	33.0	3.7	11.3	0.88	0.10	11.7	1.71	0.16	9.5
3	246	29.2	3.5	12.0	0.98	0.03	3.5	1.24	0.18	14.8
4	78	15.8	5.0	31.8	0.43	0.14	32.3	1.01	0.21	20.8
5	210	23.8	3.6	15.2	0.78	0.13	16.2	1.54	0.14	9.1
6	119	19.1	3.6	19.1	0.95	0.07	7.0	1.00	0.22	21.8

CHD_V. Clusters 2 and 3 showed slightly lower CHD_V values and were also characterized by lower dominant heights (Figures 3, 5 and Table 2). Cluster 5 had the lowest values for dominant height, CHD_V, and canopy closure, indicating vertically homogeneous stand structures with low height—seedling stands. Clusters 4 and 6 also exhibited low CHD_V values, with Cluster 4 additionally characterized by lower dominant height and canopy closure.

When comparing the proportion of plots classified according to the two methods, the seedling stands are assigned to Cluster 1 in the first analysis (CHD_{CHM}) and to Cluster 5 in the second analysis (CHD_V) (Table 3). Vertically heterogeneous stands were identified by consistently higher CHD_{CHM} and CHD_V values and a wider distribution of height classes, whereas vertically homogeneous stands showed lower CHD_{CHM} and CHD_V values concentrated

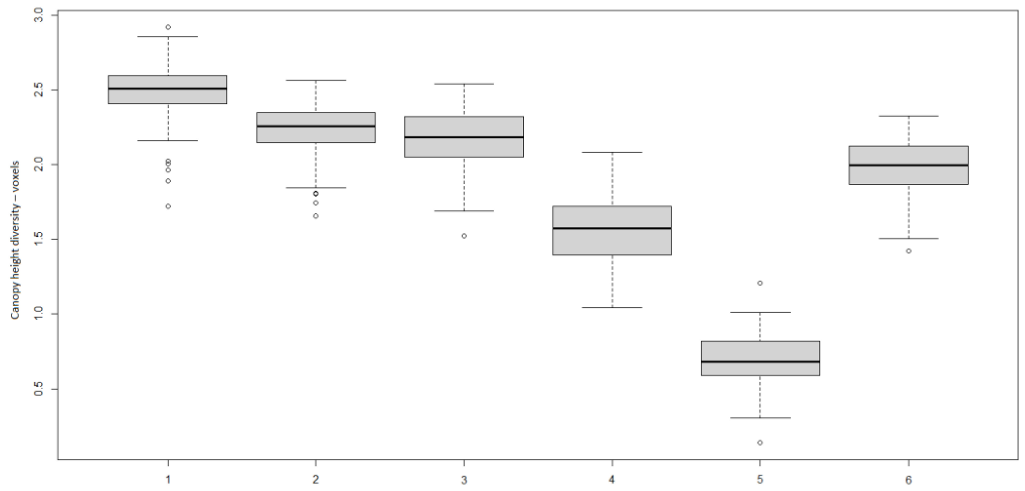


FIGURE 5
Boxplots for the CHD_V according to individual stand structure type clusters of the NFI plots.

around a dominant canopy layer. To validate the classification results, at least 20 individual stand structures from each cluster in both analyses were visually assessed on the NFI plots using the ALS-derived canopy height model (CHM), vertical cross-sections of the point cloud, and orthophotos. This confirmed that the structural characteristics inferred from the height-based metrics corresponded to the actual stand conditions in the field. Distinctly heterogeneous, uneven-aged mature stand structures are categorized as Cluster 2 in the first analysis and as Cluster 1 in the voxel-based analysis comprising 21.5% of all permanent sample plots. Vertically more homogeneous mature stands are predominantly assigned to Cluster 3 in the first analysis and Cluster 2 in the second.

The slightly higher CHD_V value in Cluster 2, compared to expectations for more vertically homogeneous mature stands, is attributed to the inclusion of understory trees in the voxel-based approach, which contributes to higher perceived vertical diversity. Vertically homogeneous pole stands with low canopy closure are consistently classified as Cluster 4 in both analyses. This concordant classification confirms that these stand types are clearly recognized by both methodological approaches. The remaining clusters represent transitional stand structure types characterized by variations in dominant heights and vertical heterogeneity.

3.2 Validation of the classification by field measurements

In both analyses, statistically significant differences were observed between the clusters for all variables ($p < 0.001$) (Tables 4, 5). In the first analysis (CHD_{CHM}), mature uneven-aged stand structures were predominantly assigned to Cluster 2. In Clusters 2 and 3, basal area, growing stock and Shannon-Wienner index fall into the same size class, and these variables are also statistically significantly different from those in the other clusters.

Interestingly, the Shannon-Wienner index exhibits similar values in both vertically heterogeneous and more homogeneous stand structures. This indicates that structurally heterogeneous stand structures contain a considerable number of understory trees beneath a dense, homogeneous upper canopy layer. These trees, which were included in the field measurements, contribute to an increased Shannon–Wiener index despite the apparent vertical homogeneity of the upper canopy.

As expected, low values for the number of trees, basal area, growing stock and Shannon-Wiener index were observed in Cluster 1, which represents seedling stands. The trees measured in these plots are remnants of the previous harvested stand. Cluster 5 represents vertically diverse stand structures at the transition from pole stands to mature stands. Clusters 4 and 6 correspond to more even- aged pole stands. The former is characterized by a low tree density and a low diameter diversity, while the latter exhibits a higher tree density and a higher diameter diversity.

In the second analysis, Cluster 1, which is structurally the most heterogeneous and has the highest dominant height, shows no statistically significant difference in the Shannon-Wiener index compared to Cluster 2, which represents mature even-aged stand structures Similar to the first analysis, this can be attributed to the presence of a considerable number of understory trees beneath an homogeneous upper canopy in Cluster 2, which are included in the field measurements and contribute to increased Shannon–Wiener index values (Table 5). This explanation is further supported by the higher CHD_V values in this cluster.

Cluster 1 displays statistically significant differences to the other clusters in terms of the number of trees and the growing stock. As expected, Cluster 5, which represents seedling stands, exhibits the lowest values for the number of trees, basal area, growing stock, and Shannon–Wiener index. In this analysis, only plots without measurable trees were included in this cluster. Cluster 3 represents the vertically more diverse stand structures at the transition from pole stands to mature stands. Clusters 4 and 6 represent even-aged pole stands, the first with low tree density and low diameter diversity, the second with higher tree density and higher diameter diversity.

Both methods of classifying stand structures yielded comparable results, although some differences were observed

TABLE 2 Number of plots, dominant height (h_{dom}), canopy closure and canopy height diversity (CHD_V) and associated standard deviations (SD) and coefficients of variation (CV) using voxels for each stand structure type cluster.

Cluster	Number of plots	h_{dom} (m)	SD_1 (m)	CV_1 (%)	Canopy Closure	SD_2	CV_2 (%)	CHD_V	SD_3	CV_3 (%)
1	247	33.8	3.4	10.1	0.91	0.08	9.0	2.50	0.16	6.4
2	345	27.0	2.9	10.6	0.94	0.06	6.7	2.24	0.16	7.2
3	96	26.2	4.9	18.6	0.61	0.12	19.8	2.18	0.20	9.2
4	68	14.0	4.5	32.1	0.37	0.16	42.3	1.56	0.25	15.9
5	37	1.9	4.5	232.5	0.02	0.03	126.2	0.70	0.21	29.7
6	158	18.6	3.1	16.4	0.89	0.11	11.9	1.99	0.17	8.8

TABLE 3 Proportional distribution of permanent plots by clusters in the assessment of canopy height diversity using CHM and voxel-based metrics.

CHM^{VOXELS}	1	2	3	4	5	6	Total
1	0.0	0.0	0.0	1.1	3.9	0.0	4.9
2	21.5	3.9	1.1	0.0	0.0	0.0	26.4
3	4.5	21.1	0.1	0.0	0.0	0.1	25.9
4	0.0	0.0	1.5	6.1	0.0	0.6	8.2
5	0.0	9.1	7.5	0.0	0.0	5.5	22.1
6	0.0	2.1	0.0	0.0	0.0	10.4	12.5
Total	26.0	36.3	10.1	7.2	3.9	16.6	100.0

TABLE 4 Number of plots, number of trees, basal area, growing stock, and Shannon-Wiener index (H) together with the corresponding standard deviations (SD), based on 2018 field measurements for each stand structure cluster identified in the first analysis (CHD_{CHM}).

Cluster	Number of plots	Number of trees (N/ha)	SD_1 (N/ha)	Basal area (m^2/ha)	SD_2 (m^2/ha)	Growing stock (m^3/ha)	SD_3 (m^3/ha)	H'	SD_4
1	6	6^{d}	13.6	1.9^{c}	4.7	23.4^{c}	57.4	0.11^{c}	0.27
2	55	468^{c}	230.2	42.4^{a}	15.9	516.0^{a}	221.6	1.36^{a}	0.32
3	53	673^{ab}	317.7	46.6^{a}	15.5	522.3^{a}	201.8	1.39^{a}	0.21
4	10	321^{cd}	243.4	13.3^{c}	11.1	121.4^{c}	113.0	0.65^{bc}	0.53
5	28	543^{bc}	336.3	33.7^{b}	17.9	357.8^{b}	201.0	1.09^{b}	0.30
6	27	915^{a}	525.2	31.7^{b}	12.8	279.0^{bc}	137.5	1.06^{b}	0.33

Statistically significant differences between clusters, as determined by Dunn's *post-hoc* multiple comparisons test, are indicated by different superscript letters.

TABLE 5 Number of plots, number of trees, basal area, growing stock and Shannon-Wiener index (H) together with the corresponding standard deviations (SD), based on 2018 field measurements for each stand structure cluster identified in the second analysis (CHD_V).

Cluster	Number of plots	Number of trees (N/ha)	SD_1 (N/ha)	Basal area (m^2/ha)	SD_2 (m^2/ha)	Growing stock (m^3/ha)	SD_3 (m^3/ha)	H'	SD_4
1	55	502^{b}	267.2	45.9^{a}	18.2	562.9^{a}	245.6	1.36^{a}	0.31
2	69	644^{a}	297.5	42.1^{a}	13.9	455.0^{b}	168.5	1.35^{a}	0.23
3	16	342^{bc}	179.1	25.7^{bc}	12.2	302.4^{c}	166.3	1.08^{b}	0.25
4	8	286^{bc}	290.8	9.4^{c}	9.0	76.2^{d}	72.5	0.47^{b}	0.46
5	5	0^{c}	0.0	0.0^{c}	0.0	0.0^{d}	0.0	0.00^{b}	0.00
6	26	950^{a}	540.8	31.7^{b}	14.2	275.5^{c}	152.7	0.99^{b}	0.34

Statistically significant differences between clusters, as determined by Dunn's *post-hoc* multiple comparisons test, are indicated by different superscript letters.

between clusters (Tables 4, 5). In the first analysis, seedling stands are categorized in Cluster 1, which includes plots with individual trees from the previous stand. In contrast, the second analysis classified only plots without measurable trees into this category. In the mature, uneven-aged stand structures (Cluster 2 in the first analysis and Cluster 1 in the second), all field-measured variables are within the same size class, although slightly higher values for tree number, basal area, and growing stock were recorded in the second analysis. In the mature, even-aged stands (Cluster 3 in the first analysis and Cluster 2 in the second), the growing stock was slightly lower in the second analysis. This difference can be attributed to a lower dominant height estimated from the ALS data for this cluster (27.0 vs. 29.2 m).

Cluster 4 in both analyses, which represents the even-aged pole stands with low canopy closure, shows the greatest difference in growing stock between the first and second analyses (121.4 vs. 76.2 m^3/ha). This discrepancy can primarily be attributed to the slightly lower dominant height and the lower canopy closure observed in the second analysis. In Cluster 6 (both analyses), which includes stands with higher tree density and greater diameter diversity compared to Cluster 4 (both analyses), all field-derived variables are classified in same size class. For Clusters 5 in the first and 3 in the second analysis, the Shannon-Wiener index is in the same size class. However, the number of trees, the basal area and the growing stock are substantially lower in Cluster 3 (second analysis) than in Cluster 5 (first analysis). The two methods differ considerably in this classification. The second method also classifies a considerable number of stands with low canopy closure into this cluster, which results in lower stand density values. The observed differences are primarily due to the fact that these two clusters represent stand structures at transition from pole to mature stands, characterized by a pronounced vertical heterogeneity. In this cluster, the first analysis includes more stand structures with higher dominant height and canopy closure, while the second analysis includes more stand structures with lower dominant height and canopy closure.

Caution is required when interpreting the validation results for Clusters 1 and 4 in the first analysis and Clusters 4 and 5 in the second analysis due to the limited number of sample plots (10 or fewer plots per group). Nevertheless, the consistency of the results—especially the low values for dominant height, canopy closure, and both CHD_{CHM} and CHD_V—for these clusters supports the validity of the classification. This is particularly evident in the seedling stands with the fewest plots (six and five, respectively), where the measured field variables are consistent with the expected structural characteristics. Therefore, the validation can be considered reliable despite the small sample size.

4 Discussion

In the present study, we analyzed the detection of uneven-aged and even-aged forest stand structures on NFI permanent sample plots using freely available national low spatial resolution (5 points per m^2) airborne laser scanning data. Understanding the spatial distribution of uneven-aged forests is particularly important as these forests are more resilient and resistant to disturbance and climate change. A comprehensive understanding of both vertical and diameter heterogeneity in uneven-aged stands is crucial for improving their adaptive capacity. While diameter heterogeneity has been intensively investigated through field-based measurements of tree diameters (Kotar, 2011; Pintar and Hladnik, 2018), this study contributes by providing a field-independent assessment of vertical structural heterogeneity based solely on ALS data. Furthermore, identifying the location and vertical structural indicators of even-aged stands is equally important as it supports informed decision making for future forest management plans to improve forest resilience and resistance under changing climatic conditions.

The use of tree height metrics and indicators to describe tree canopy cover and vertical heterogeneity derived from ALS data has already been demonstrated as effective for classifying stand structures or forest stands, both at the level of whole stands and individual sample plots (Pascual et al., 2008; Torresan et al., 2016; Pintar and Skudnik, 2024a; Pintar and Skudnik, 2025). In our study, both variants of the K- means clustering approach (CHM and voxels), resulted in an optimal number of six clusters, as determined using the elbow method and visual assessment of stand structure patterns within each cluster. Similar results were reported in studies of structurally heterogeneous forests in central Spain (Pascual et al., 2008), northern Italy (Torresan et al., 2016) and Slovenia (Pahernik Estate, Pohorje) (Pintar and Skudnik, 2024a), where the optimal number of clusters derived from ALS data using the K-means method was five or six, which is consistent with the results of the present analysis.

We used CHM and voxel-based metrics derived from ALS data to estimate the vertical heterogeneity of forest stand structures. The CHM method was selected due to its simplicity and ease of implementation (Kim et al., 2016; Fassnacht et al., 2024), while the voxel method was used due to its great potential to improve the accuracy of forest structure description and stand characterization analysis (Pearse et al., 2019). Both methods provided equivalent results for stand structure classification, although the differences in vertical diversity between the uneven-aged and even-aged stands were more pronounced when CHM was used. Therefore, in areas with low-density ALS data, CHM analysis appears to be a more appropriate approach for assessing vertical heterogeneity. These findings are consistent with previous research from the Pohorje region, where CHD_{CHM} values for mature uneven-aged stands, calculated at the level of whole stands across a 570 ha forest estate, were estimated at 1.83 and 1.86 (Pintar and Skudnik, 2024a), closely matching the value obtained in this study (1.71). However, the usefulness of voxels is confirmed by the fact that the voxel method classifies 21.5% of the 26.0% of NFI plots (Table 3) as the stand structures with the highest vertical heterogeneity (uneven-aged). In this study, the terms "uneven-aged" and "even-aged" refer to the degree of vertical canopy differentiation, validated with field measurement data. To also validate the classification results, at least 20 individual stand structures from each cluster in both analyses were also visually assessed on the NFI plots using the ALS-derived canopy height model (CHM), vertical cross-sections of the point cloud, and orthophotos. This visual inspection confirmed that the structural characteristics inferred from the canopy height diversity metrics corresponded well with the actual stand conditions observed in the field.

For higher density ALS datasets, the use of voxel-based approaches (Pearse et al., 2019) are recommended, as they allow the detection of shade-tolerant understory trees. The resilience of stands to natural disturbances is mainly influenced by the vertical heterogeneity of trees in the canopy (Senf et al., 2020), which is effectively recognized by the CHD_{CHM} based classification method (Pintar and Skudnik, 2024a). We can state with high confidence that voxel-based approaches will be more appropriate in future studies using high-density ALS data. These methods are particularly effective for analyzing vertical structural diversity in characteristically multi-layered forest types, such as lowland floodplain oak–hornbeam forests (Hladnik and Pintar, 2017) and selection fir–beech forests (Bončina et al., 2002). The voxel-based analyses and the corresponding results presented in this study provide a valuable basis for further research into the vertical structure of forests using freely available national ALS datasets, which are expected to be recorded at higher point densities in the future.

In the Alpine and Pohorje ecological regions, ALS data were acquired in 2014 and 2015, while the field measurements on permanent sample plots were conducted in 2018. Despite the slightly longer time interval between the two data sets, the field measurements are still suitable for validating stand structure classification based on ALS data, as this type of comparison has already been applied at the national level (Skudnik et al., 2022b). This is also supported by the fact that harvesting occurred on 29% of all plots in the Alpine and Pohorje ecological regions between 2012 and 2018—a period that is 2–3 years longer than the period between the ALS survey (2014–2015) and the National Forest Inventory (2018). On the vast majority of plots where harvesting occurred, only individual trees were removed, which does not significantly affect the comparability of the data sets. Only 2% of the plots were more than two thirds of the trees harvested. The validation is also not significantly affected by tree height growth, as spruce trees at approximately 900 m a.s.l. in this area exhibit an annual height increment of 28–40 cm (Kotar, 2011).

The validation of stand classification using field measurement data was successful, as statistically significant differences in stand variables (derived from field measurements) were found between stand structure types classified from ALS data based on vertical heterogeneity and dominant height. The variables used in the analyses are also used in other national forest inventories in Europe. Therefore, the proposed methods can also be applied on a larger scale, which is particularly important given the increasing global need for a “living forest inventory” (Coops et al., 2022) that can capture forest dynamics in near real time. Europe is still dominated by even-aged forests (ForestEurope, 2020). In times of climate change, the aim is to improve the resilience and resistance of these forests, which can be achieved by increasing forest heterogeneity (O’Hara and Ramage, 2013; Senf et al., 2020). Therefore, an increase in the proportion of uneven-aged forests is expected in Europe and beyond (Dănescu et al., 2016; Dănescu et al., 2017).

All methods and analyses presented in this study are transferable and can be applied in future studies across other Slovenian forests as well as well as in forests outside the Slovenian borders. They are applicable in both uneven-aged and even-aged forests. In the latter, it will be easier to monitor a possible increase in vertical heterogeneity, which is particularly important in times of climate change, as uneven-aged forests are much more resilient. The applicability of the proposed methods largely depends on the availability of ALS data, which has become increasingly available across European countries in recent years (Pintar and Skudnik, 2025; Pintar and Skudnik, 2024b; Pintar, 2025). When applying these methods in other regions, including other Slovenian forests or international contexts, it is important to check the key parameters (the radius used for treetop identification, the height class interval for calculating canopy closure, and the *CHD* index) and adjust them if necessary to take local forest stand conditions into account. The parameter values used in this study (e.g., the 3 m window radius for local maxima detection, 5 m height class width, and 5 m canopy-closure threshold) were selected to match the prevailing crown architecture of the study area, where trees typically have tall, narrow crowns with moderate vertical stratification. These values should not be considered universal. In forests where crowns are wider, more irregular, or strongly overlapping—such as many broad-leaved or tropical forest types—optimal parameterization may differ to accurately capture individual treetop positions and canopy layering. The classification framework remains transferable, but parameter values should be adjusted to canopy architecture to ensure that canopy height diversity reflects structural differences rather than species-specific crown form. For example, in predominantly coniferous stands, where tree crowns are narrower and more steeply tapered, a smaller search radius may be suitable for detecting treetops, while in stands with broadleaves, a larger radius may be needed to accurately identify local maxima.

Although the classification approach based on canopy height diversity successfully differentiated vertically heterogeneous from more homogeneous stand structures, some limitations should be acknowledged. The *CHD* metrics used in this study describe the vertical distribution of canopy elements; therefore, their interpretability depends on the extent to which different canopy layers are detectable in the ALS point cloud. In stands where stratification is strong and continuous, canopy height diversity values clearly reflect these differences. In contrast, in stands where stratification is less pronounced, spatially patchy, or transitions between layers are gradual, structural gradients may be more subtle, and the resulting classification boundaries less distinct. For this reason, the classification results should be interpreted as a continuum of structural conditions rather than discrete stand types. Future applications may benefit from integrating canopy height diversity with additional descriptors of horizontal tree arrangement or stand density, which could further refine the detection of intermediate structural classes. Furthermore, separating stands prior to classification based on their species composition (e.g., predominantly coniferous, predominantly broadleaved, and mixed stands with varying degrees of mixture) could improve parameter selection, such as the search radius used for local maxima detection. This could be efficiently achieved using high-resolution satellite or airborne multispectral imagery to pre-classify plots before structure classification. The results presented here apply specifically to mixed spruce–fir–beech forests in the Alpine and Pohorje ecological regions. The canopy height diversity metrics quantify vertical stand structure and are therefore not directly affected by factors such as elevation or parent rock; however, these site conditions may influence long-term stand development and should be considered when applying the classification framework in different environmental conditions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AP: Conceptualization, Writing – review & editing, Validation, Investigation, Funding acquisition, Project administration, Software, Writing – original draft, Formal analysis, Resources, Data curation, Visualization, Methodology.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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