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Assessing forest structure with LiDAR: A method benchmark in the Rohrach Natural Forest Reserve

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ABSTRACT

The Rohrach Natural Forest Reserve, located in the northern foothills of the Alps, serves as a long-term reference area for preserving and studying natural forest development. In this study, three methods for assessing forest structure—classical field-based inventory, terrestrial laser scanning (TLS), and drone-based LiDAR (UAV-LS)—were systematically compared. Building on an initial survey conducted in 1996, 44 sample plots were revisited and supplemented with high-resolution 3D measurements.

The results show that TLS provides highly accurate volume estimates that closely match those obtained through the classical inventory. The UAV-based approach enabled a comprehensive, area-wide survey of the 48-ha study site and yielded average growing stock values of 547 m³/ha—almost identical to those from the classical inventory (549 m³/ha). However, automated detection of lying deadwood using UAV data underestimated the volume by up to 50% compared to the line intersect method. Whether this discrepancy is due to the line intersect method's assumption of randomly distributed logs being unsuitable for this site, or whether UAV-LS underestimates deadwood due to canopy shadowing or algorithmic omission of fine structures, requires further investigation.

The study also highlights persistent challenges in tree segmentation within steep or densely vegetated areas: overlapping crowns often result in misclassifications or undetected stems. While TLS continues to offer the highest geometric accuracy, UAV-LS provides the advantage of rapid, large-scale data acquisition with minimal disturbance to sensitive environments.

These findings underscore the importance of integrated methodological approaches for effective long-term monitoring in natural forest ecosystems.

KEYWORDS

- forest structure analysis
- Rohrach Natural Forest Reserve
- method bench-marking
- TLS
- LiDAR
- UAV
- Deadwood
- large woody debris
- growing stocks
- beech forest

Einsatz von LiDAR in der Waldstrukturanalyse: Methodenbenchmark im Naturwaldreservat Rohrach

ZUSAMMENFASSUNG

Das Naturwaldreservat Rohrach im nördlichen Alpenvorland dient als langfristiges Referenzgebiet zur Untersuchung der natürlichen Waldentwicklung. In dieser Studie wurden drei Methoden zur Erfassung der Waldstruktur – klassische terrestrische Inventur, terrestrisches Laserscanning (TLS) und drohnenbasiertes LiDAR (UAV-LS) – systematisch verglichen. Aufbauend auf einer Ersterhebung aus dem Jahr 1996 wurden 44 Stichprobeflächen erneut untersucht und durch hochauflösende 3D-Messungen ergänzt.

Die Ergebnisse zeigen, dass TLS sehr präzise Volumenschätzungen liefert, die mit der klassischen Inventur nahezu übereinstimmen. Die UAV-gestützte Methode wiederum ermöglichte eine vollständige flächenhafte Erhebung des 48 Hektar großen Untersuchungsgebiets und ergab mit durchschnittlich 547 m³/ha nahezu identische Vorratswerte wie die klassische Erhebung (549 m³/ha). Die automatische Erfassung von liegendem Totholz mittels UAV unterschätzte jedoch das Volumen um bis zu 50 % gegenüber der Line-Intersect-Methode. Ob die Line-Intersect-Methode, die von einer zufälligen Verteilung der Baumstämme ausgeht, für dieses Gebiet ungeeignet ist, oder ob die UAV-LS-Auswertung das Totholz aufgrund von Abschattungen unter dichten Kronendächern bzw. algorithmisch bedingten Auslassungen feiner Strukturen systematisch unterschätzt, muss in einer weiterführenden Untersuchung geklärt werden.

Zudem wird deutlich, dass Baumsegmentierungen in steilen oder dichten Beständen problematisch bleiben: Überlappende Kronenbereiche führen zu Fehlklassifikationen und übersehenen Stämmen. Während TLS nach wie vor die höchste geometrische Genauigkeit bietet, hat die UAV-LS Methode den Vorteil der flächendeckend, zeitsparenden Erfassung und der geringeren Störung empfindlicher Standorte.

Die Ergebnisse betonen die Bedeutung integrierter Methodenansätze für ein effektives Langzeitmonitoring in Naturwäldern.

INTRODUCTION

The 47.5-ha Rohrach Natural Forest Reserve (Figure 1) was established in 1992 and represents a characteristic forest ecosystem of the flysch-dominated Molasse zone in the northern fringe of the Alps. As a long-term unmanaged forest, it serves as an important ecological reference site – both for observing natural forest development processes

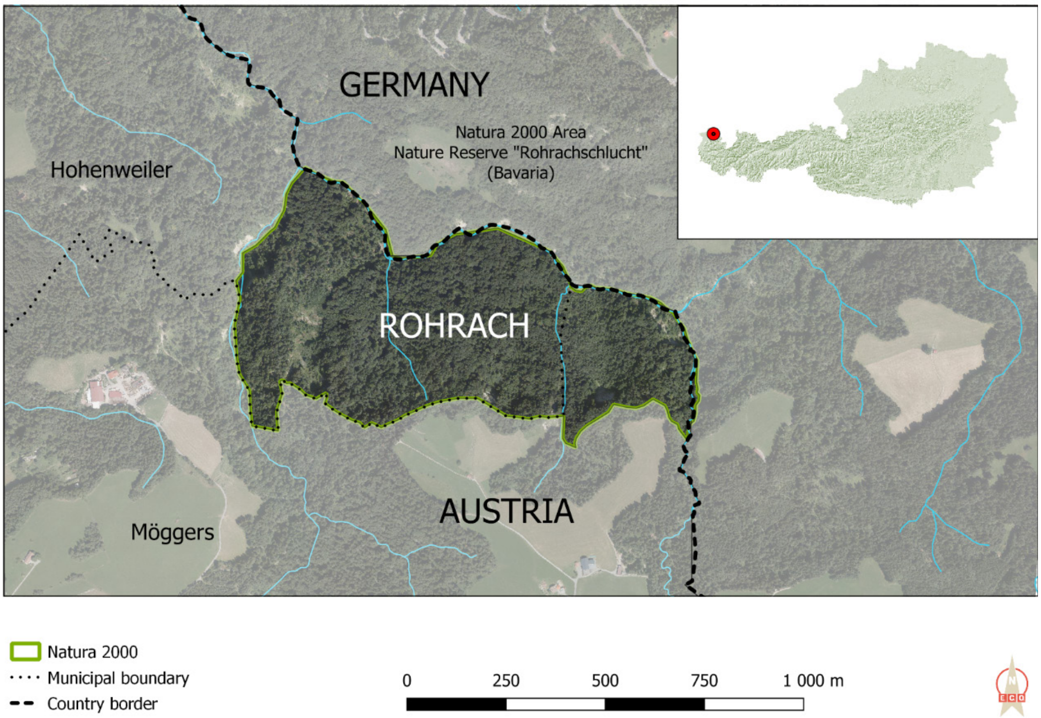

Fig. 1

Figure 1: Study area: Rohrach Natural Forest Reserve

Abbildung 1: *Untersuchungsgebiet Naturwaldreservat Rohrach*

and for deriving potential transformation pathways for managed production forests on comparable site types.

In recent years, the ecological and societal relevance of such natural forests has gained increasing attention. Against the backdrop of the global climate crisis and accelerating biodiversity loss, forests are recognized as multifunctional ecosystems of critical importance [1], [2], [3], [4], [5]. The EU Biodiversity Strategy highlights the need to exclude natural forests from utilization to secure their functions as biodiversity hotspots, carbon sinks, and long-term reference areas. Particularly in the context of the Paris Climate Agreement, forest's role in carbon sequestration and storage has become a key variable in achieving emission reduction targets.

One increasingly important concept in this context is "proforestation" – the deliberate promotion of natural forest development to maximize carbon storage, biodiversity, and other ecosystem services [6], [7]. A central question for policymakers and forest managers is how the structural transformation from managed forests to natural forests affects carbon stocks and other ecosystem functions such as recreation, protection, water retention, and biodiversity [8], [9].

In 1996, an extensive structural and geobotanical baseline survey was conducted in the Rohrach Natural Forest Reserve under the direction of Grabherr et al. [10]. The study included transect-based vegetation surveys as well as a systematic forest structure inventory on a 100 × 100 m grid, documenting tree species, deadwood, and rejuvenation. This dataset laid a solid foundation for long-term scientific monitoring of forest development following cessation of management.

In 2022, this baseline was revisited through a joint research initiative by E.C.O. Institute of Ecology and TU Wien [11]. The objective was to evaluate the performance and applicability of modern forest structure analysis methods by directly comparing them with classical inventory techniques. In addition to traditional field-based sampling, two digital technologies were tested: terrestrial laser scanning (TLS) at sample plots and high-resolution drone-based LiDAR (UAV-LS) for airborne 3D data acquisition. These

technologies enable highly detailed structural mapping of above-ground biomass, including canopy architecture, stem volume, and branch mass – particularly valuable for assessing carbon stocks in broadleaved forests [12], [13], [14], [15], [16].
Combining long-term baseline data with state-of-the-art 3D scanning techniques opens new opportunities for tracking structural and biomass changes in short monitoring cycles of 3 to 5 years. This positions the Rohrach Natural Forest Reserve not only as a reference area for natural forest dynamics, but also as a European model site for carbon stock monitoring in unmanaged forests – with a significant temporal advantage over newly designated reference areas.

METHODS

As outlined in the introduction, the forest structure survey originally conducted by Grabherr et al. [10] in 1995-96 was repeated in 2022. In the course of the follow-up study, three different methods were applied and systematically compared. These methods were:

1. classical field-based forest inventory,
2. TLS conducted within the forest, and
3. drone-based laser scanning.

In the classical field-based approach, a 100 × 100 m grid was overlaid across the entire area of the forest reserve. At each grid intersection, a sample plot was established, resulting in a total of 44 sampling locations. The center of each plot was originally marked in 1995-96 by a wooden post. In about 2/3 of the plots, this post was found again. When no post was found, GPS coordinates were used to identify the plot location.
TLS was conducted in 18 of the 44 sample plots. Due to the steep and slippery terrain in parts of the reserve, it was not feasible to transport and operate the approximately 17-kg TLS device in all locations. The complete sampling grid is shown in Figure 2. Sample plots where TLS data were successfully collected are highlighted in yellow. UAV-LS was carried out across the entire area of the reference site.

Classical field-based forest inventory

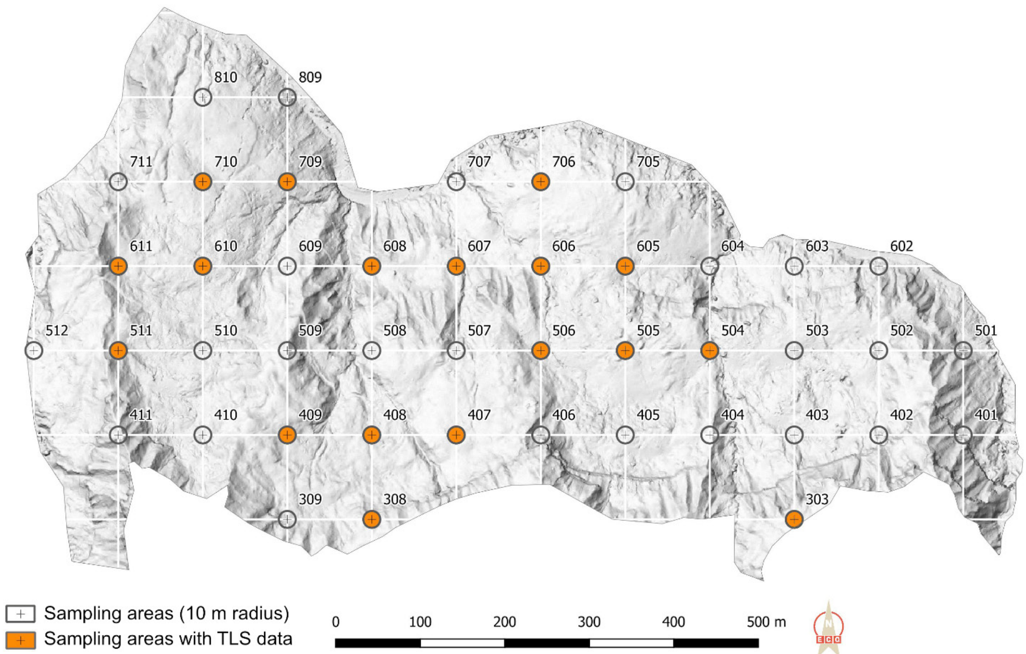

Fig. 2

Figure 2: Sampling Areas, Source: sampling grid by Grabherr et al. [10]

Abbildung 2: *Testgebiete, Quelle: Stichprobenraster übernommen von Grabherr et al. [10]*

In the classical field-based approach at each of the 44 sample areas, all trees within a 10-meter radius of the plot center were recorded. The collected data included the relative position of each tree position (angle and distance to the center of the sample), tree species, vitality status (alive or dead), and diameter at breast height (DBH). Tree height was not recorded in the field, as height measurements were later derived from TLS data. This decision was made because TLS provides significantly more accurate height estimates compared to measurements taken with a conventional forestry laser rangefinder [17].
Based on the collected field data (DBH and TLS-derived tree height), tree volume was estimated using the Denzin formula, a forestry-specific approach that incorporates height, diameter, and species-dependent form factors. This formula is used to estimate merchantable trunk volume, rather than total tree biomass. This includes timber with a diameter larger than 7 cm.
To improve height estimates for plots without TLS data, linear regression models were developed using measurements from the 18 TLS-scanned plots. The models describe the relationship between DBH and tree height using the Peterson transformation, which stabilizes variance and improves linear fit. The transformed variables were defined as:

$x = 1/DBH$ and $y = \frac{1}{\sqrt{Height-1,3}}$

Species were grouped to ensure sufficient sample sizes for regression analysis. After removing outliers caused by TLS errors or structural tree damage, regression models of the form:

$$y = b * x + a$$

were used to predict tree heights in the remaining 26 plots. These estimated heights, along with measured DBH, were then used in the Denzin formula (Table 1):

$$Vol = \left(\frac{DBH^2}{1000}\right) + \frac{DBH^2}{1000} * (Height - Hnorm) * Vol\_Corr$$

Vol = volume in m^3 of timber > 7cm diameter
DBH = Diameter at breast height in cm
Height = height of sample tree in m
Hnorm = Norm height calculated based on the tree species and the DBH

Tab. 1

Tree species	Hnorm (m)	Vol_Corr
spruce (*Picea abies*)	19+2*DBH (dm)	4%
larch (*Larix decidua*)	17+3*DBH (dm)	5%
fir (*Abies alba*)	21+DBH (dm)	4%
pine (*Pinus sylvestris*)	28	3%
beech (*Fagus sylvatica*)	25	3%
All other deciduous trees	25	3%

Table 1: Parameters to calculate norm height and correction factors for tree species

Tabelle 1: *Parameter zur Berechnung der Norm-Höhe und des Korrekturfaktors.*

In addition to recording standing live trees, the field inventory also included an assessment of lying deadwood. To quantify this, the line intersect sampling method was applied. Originally developed in North America to evaluate the fire hazard of forest floor fuels [18], this method records any piece of downed deadwood that intersects a transect line and meets or exceeds a defined minimum diameter at the point of intersection—regardless of the piece's total length. The method has already been implemented in European forest inventories, e.g., [19].

Importantly, deadwood pieces do not need to be in contact with the ground to be recorded. Fragments that cross the transect several meters above ground, such as branches from a recently fallen crown, are also included. Additionally, dead trees leaning more than 45° from the vertical axis are classified as downed and are recorded if they intersect the transect. If a single piece of wood intersects the transect line multiple times (or intersects more than one line), each crossing is counted. Trunks that run exactly along a transect (i.e., their longitudinal axis aligns with the line) or merely touch it without intersecting the centerline are not recorded—though these cases are rare.

In this study, two 40-meter transect lines were established per plot. The transects were arranged perpendicularly and intersected at the plot center, forming a cross-shaped layout with a total sampling length of 80 meters, as recommended by Fraver et al. [20]. On sloped terrain (slope > 5%), one transect was aligned parallel to the contour lines, while the other followed the slope line (upslope and downslope). In flat terrain (slope < 5%), the transects were oriented along cardinal directions: north–south and east–west.

In our fieldwork, it proved practical to work with true distances (slope distances) measured in whole meters. Thus, four transect segments of 20 meters each were laid out from the center point in the four cardinal directions (Figure 3). For horizontally aligned segments, the slope distance corresponded to the projected horizontal length. For upslope and downslope segments, slope was taken into account to correct for horizontal projection (using the cosine of the inclination angle), meaning that the effective transect length was reduced to ensure that volume estimates per hectare of horizontal surface area remained accurate.

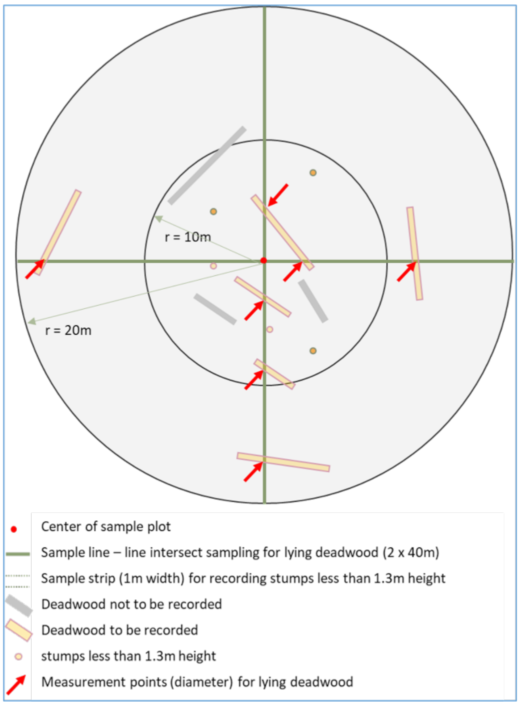

Fig. 3

Figure 3: Line intersect method, Source: E.C.O. according to [18]

Abbildung 3: *Line-intersect Methode, Quelle: E.C.O. nach [18]*

All downed woody fragments with a diameter ≥10 cm at the point where their imaginary centerline intersects the transect were recorded. The following attributes were measured:

- Diameter (in cm) at the intersection point (measured perpendicular to the stem axis)
- Tree species (in advanced decay stages categorized as coniferous, broadleaved, or unidentified)
- Decay class (five-stage classification)
- Origin: cut, broken, or windthrown

Windthrow was identified by the presence of a root plate or exposed roots. In addition, all stumps and cut stems under 130 cm in height within a 20-meter radius from the plot center were recorded. For each, the following parameters were documented: diameter, tree species, and decay class.

The following formula was used to calculate the biomass [18]:

$$V_{LG} = \frac{\pi^2 \sum_{l=1}^{i} d_L^2}{8L}$$

V_{LG} = Volume of lying deadwood
d_L = diameter in cm of the cross-sectional area of the i-th lying tree trunk l with a central diameter > 10 cm

Terrestrial laser scanning

To estimate standing tree volume using TLS, 18 of the 44 sample plots were scanned. Due to steep and inaccessible terrain, TLS data collection was not feasible at all locations.
Each of the selected plots was scanned using a VZ-400i terrestrial laser scanner (RIEGL Deutschland Vertriebsgesellschaft mbH, Gilching bei München, Germany). The instrument provides a ranging accuracy of approximately 5 mm and a precision of about 3 mm (1σ at 100 m under standard manufacturer test conditions), which ensures highly reliable distance measurements even in complex field environments. From approximately 10 to 20 scan positions per plot, a full 3D point cloud of all trees and the shrub layer within a 30-meter radius of the plot center was captured, allowing for detailed structural documentation.
The processing and analysis of the TLS point clouds were conducted by Forest Design SRL (Brașov, Romania). For each individual tree, quantitative structure models (QSMs) were generated by fitting cylindrical elements to the tree's point cloud (Figure 4). Based on these models, the stem volume of each tree was calculated. Subsequently, plot-level volume values were scaled to a per-hectare basis to allow for direct comparison with other inventory methods.

Fig.4

Figure 4: Fitting cylinders in the trunk to determine the volume, Source: Forest Design SRL

Abbildung 4: *Einpassen von Zylinder in den Stamm zur Volumen-Ermittlung, Quelle: Forest Design SRL*

Drone-based laser scanning

The entire study area, covering 48 ha, was surveyed using a drone-mounted LiDAR system combined with a high-resolution camera. The system consisted of a VUX-120 laser scanner (RIEGL Deutschland Vertriebsgesellschaft mbH, Gilching bei München, Germany) and an iXM100 camera (Phase One A/S, Frederiksberg, Denmark), both mounted on a LasCO 2 multicopter (Soleon GmbH, Varna, Italy). The VUX-120 provides a ranging accuracy of approximately 10 mm and a precision of about 5 mm (1σ at 100 m under standard manufacturer test conditions). The aerial survey was conducted by Alto Drones (South Tyrol, Italy) in April 2022 under leaf-off conditions to ensure optimal visibility of ground and understory structures, and TLS took place under similar conditions. The

average point density of the laser scan flight exceeded 4,200 points per square meter. The resulting 3D point clouds were processed in the ETRS89 / UTM Zone 32 coordinate system with orthometric heights, calculated using the official geoid model provided by the Austrian Federal Office of Metrology and Surveying (BEV). To ensure accurate georeferencing, the area was flown in overlapping parallel flight lines with additional cross-strip flights, improving spatial consistency and coverage (Figure 5).
At TU Wien, the total aboveground biomass for the entire study area was estimated using an approach analogous to the TLS-based method. Cylindrical models were fitted to the tree trunks within the UAV-derived 3D point cloud to reconstruct individual tree volumes.

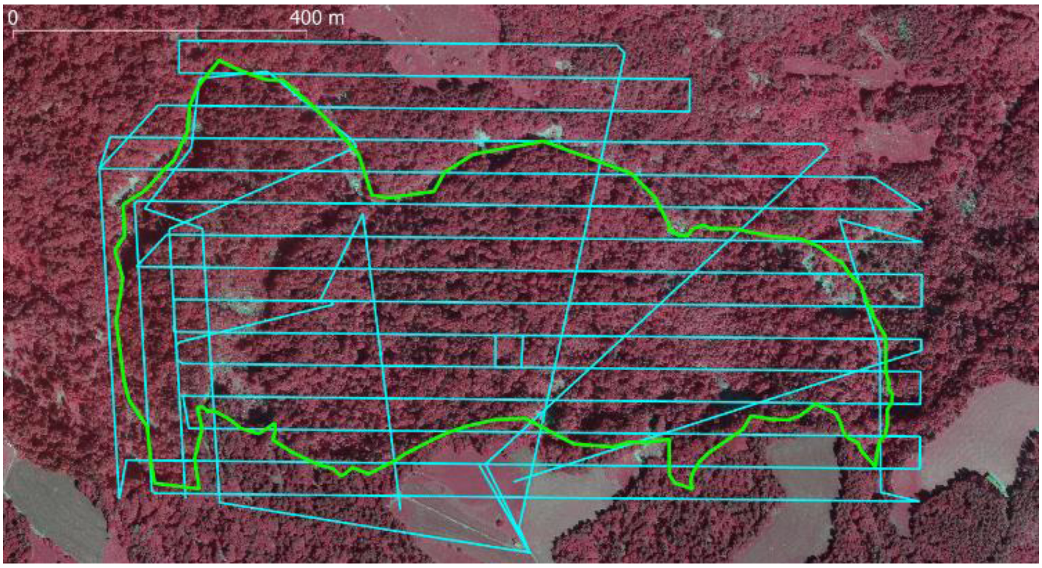

Fig. 5

Figure 5: Flight trajectories, Source: TU Wien (Markus Hollaus)

Abbildung 5: *Flugtrajektorien, Quelle: TU Wien (Markus Hollaus)*

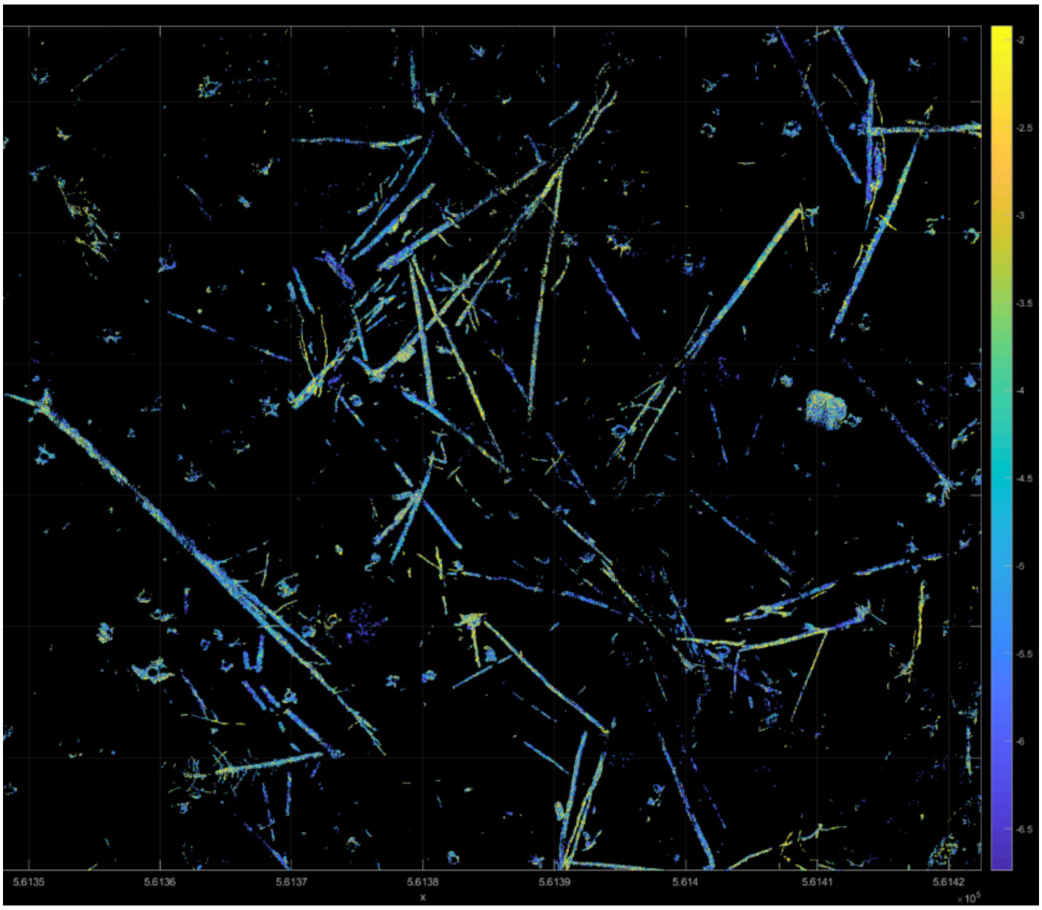

Fig. 6

Figure 6: UAV-LS – Lying deadwood detection, Source: TU Wien (Markus Hollaus)

Abbildung 6: *UAV-Laserscanning – Detektion des liegenden Totholzes, Quelle: TU Wien (Markus Hollaus)*

In addition, an automated analysis of lying deadwood was carried out (Figure 6). Detection was based on a knowledge-based decision tree, applied to the normalized point cloud. The algorithm incorporated both geometric and radiometric properties of the LiDAR points to distinguish deadwood elements from other structures. The analysis focused on near-ground deadwood segments located up to 5 meters above ground level. Once identified, the volume of lying deadwood was estimated using a voxel-based approach with a voxel resolution of 5 × 5 × 5 cm³.

Some limitations were noted in areas with overlapping trunks or gaps in the point cloud, for example due to occlusions or shadowing effects during scanning. In the case of several vertically overlapping lying stems only the top-most stem is considered for the deadwood volume estimation. Furthermore, this method only considers horizontal distances, which may lead to an underestimation of deadwood volume if the stems are lying on steep terrain.

RESULTS

Standing stock volume

The calculation of standing volume per hectare (including live and dead wood) based on TLS data from 10-meter-radius plots yielded results closely aligned with those derived from the classical field-based inventory (Table 2). The difference between the two methods was only 24 m³/ha. In some cases, there are significant discrepancies between individual plots when comparing the results of traditional inventory methods with TLS analysis (e.g., Plot 511, Plot 710). One possible cause could be insufficient spatial accuracy in plot positioning. A slight displacement of the plot center (different center depending on the method), and thus the entire plot, can lead to the inclusion of different trees. If these trees have a large DBH, this can consequently impact volume estimates.

Tab. 2

Plot Nr.	m³/ha Classic inventory sampling in the field (10 m radius)	m³/ha TLS (10 m radius)	m³/ha TLS (20 m radius)
303	416	476	590
308	1321	1149	759
407	826	795	791
408	124	150	491
409	464	416	656
504	687	669	748
505	1066	845	740
506	731	893	588
511	790	289	351
605	715	1060	816
606	357	651	728
607	668	676	845
608	824	758	753
610	119	194	172
611	635	844	665
706	1612	1462	874
709	786	745	543
710	397	43	755
Average volume/ha	**697**	**673**	**659**

Table 2:
Comparison of field sampling and TLS methods: Volume (m³) of standing (living and dead) trees per hectare across 18 forest inventory points

Tabelle 2:
Vergleich Klassische Stichprobeninventur im Gelände und TLS: Volumen stehender (lebender und toter) Bäume pro Hektar in 18 Waldinventurpunkten Norm-Höhe und des Korrekturfaktors.

Additionally, Plot 710 represents an open forest area with few trees within the 10-meter radius. However, as the radius increases, several large tree trunks become part of the sample. When looking at all plots collectively, these spatial accuracy deviations appear to balance out across the dataset.

When all 44 classical inventory plots are considered, the total average volume is slightly lower—549.27 m³/ha - compared to 697 m³/ha in the 18 TLS-sampled plots (standing living and dead). This approximately 27% higher value in the TLS subset is primarily due to the fact that TLS data were collected in fully stocked forest areas, whereas the full dataset includes plots on landslide zones dominated by pioneer forests with lower biomass.

To assess the effect of sample area size, standing volume per hectare was also calculated using 20-meter-radius TLS plots, thus quadrupling the sampled area. Interestingly, this larger sampling area resulted in a mean volume per hectare that differed by only 2 % compared to the 10-meter plots. This indicates that the 10-meter-radius plots provide a representative estimate of forest volume for the study area.

In addition to the TLS-based assessment, TU Wien also calculated standing live and deadwood volume using drone-based LiDAR data. This approach covered the entire 48-ha area of the natural forest reserve, including fully stocked forests, pioneer forests on landslides, and open landslide areas.

The mean volume per hectare derived from the UAV-LiDAR data was **547.42 m³/ha,** which matches closely with the **549.27 m³/ha** (standing living and dead) obtained from the 44 manually recorded inventory plots. This strong agreement underscores the reliability of UAV-LiDAR for large-scale forest volume assessments.

Deadwood estimation

One major advantage of UAV-based deadwood analysis is the ability to automatically and operationally detect deadwood, even in areas where it is barely visible from above. Despite the presence of classification artifacts—such as outlines of rocks or terrain features mistakenly identified as deadwood—the average volume of lying deadwood derived from the UAV analysis was nearly 50% lower than the estimate obtained using the line intersect method (Table 3).

Tab. 3

	Average lying deadwood (m³/ha)		
Type	**Field survey**	**UAV in relation to total area of the Rohrach Natural Forest Reserve (47.5 ha)**	**UAV related to the 10 m radius plots**
Lying deadwood	99.6	55.9	45.8
Standing deadwood	39.97	N/A	N/A

Table 3: Comparison of deadwood classic sample inventory and UAV evaluation

Tabelle 3: *Vergleich liegendes Totholz klassische Stichprobeninventur und UAV-Auswertung*

Time resources

Additionally, the study also evaluated the time resources required for each inventory method (Table 4). A significant advantage of laser scanning technologies—particularly UAV-LS—is the ability to collect data remotely, without the need for extensive on-site fieldwork.

Tab. 4

Method	Time (in the field)	Sample Size
Classical field-based forest inventory (44 plots)	170 h (field work)	All trees within a 10 m radius of the sample center
TLS (18 plots)	25 h (including moving from one plot to the next)	All trees within a 30 m radius of the sample center
UAV	16 h (2 people, one day)	Full test area

Table 4: Comparison the time resources required for each inventory method

Tabelle 4: *Vergleich der Zeitressourcen je nach Erhebungsmethode*

While traditional field-based inventories are labor-intensive and time-consuming—requiring physical access to each plot and manual measurements for every tree—UAV-LS enables rapid data acquisition over large and inaccessible areas. A single drone flight can cover the entire study area in a fraction of the time, often producing results of equal or even higher precision compared to manual measurements.

This reduction in field effort not only improves operational efficiency, but it also minimizes disturbance to sensitive natural habitats—making UAV-LS a compelling option for modern forest monitoring.

DISCUSSION

Structural Characteristics and Biomass Dynamics of the Rohrach Natural Forest Reserve

From 1996 to 2022, the living growing stock increased from 426 m³/ha [10, p. 55] to 509 m³/ha (traditional method, 44 plots, standing living trees only) in 2022. It is likely that the forest stands in Rohrach had not yet reached an equilibrium in 1996 like in a natural forest ecosystem. This is underpinned by the fact that the deadwood volume increased over the same interval from 49 m³/ha (1996) to 141 m³/ha (2022, standing and lying). The volume of living and dead biomass is higher than in most natural beech forest habitats in the Kalkalpen National Park of Austria (247 m³/ha living, 25 m³/ha deadwood) [21] but less than in the comparable primeval beech forests Uholka-Shyrokyi Luh in Ukraine (582 m³/ha living, 163 m³/ha deadwood) [22]. The forest reserve in Rohrach is characterized by extensive landslides, which leads to a significant portion of areas (12%) that are not covered by forests. The soft shist, marl and flysch bedrock increase the likelihood of windthrow, which, together with the landslides, might be an explanation of the exceptionally high deadwood volumes.

A standing timber volume of 547.42 m³/ha, or 549.27 m³/ha based on UAV analysis, is characteristic of an undisturbed natural forest. This large volume indicates a dense, structurally complex, and highly productive forest ecosystem. The forest stands in the Rohrach Natural Forest Reserve are notable for their high proportion of standing deadwood, massive old trees, and multilayered canopy structure.

Current challenges in methodologies for the assessment of standing biomass

The comparison of the three methods confirmed findings from previous studies [23], highlighting that among all terrestrial point cloud techniques, TLS still provides the highest data quality in terms of geometric accuracy and level of detail. However, a consistent challenge for all terrestrial point cloud data is the occlusion in the upper canopy layers.

UAV-based laser scanning offers a promising alternative by potentially combining the advantages of both above- and below-canopy measurements. As demonstrated by Liang et al. [24], UAV-LS point clouds can perform comparably to terrestrial methods under favorable stand conditions. While the geometric precision of UAV-LS (particularly in the stem region) does not yet match that of TLS, the method's high mobility and rapid data acquisition make it a highly attractive option for forest inventories [24].

In the study by Pitkänen et al. [25], it is pointed out that stem volume estimates derived from automated cylinder or circle fitting are often compromised by registration errors and occlusions—i.e., parts of the stem that are only partially visible.

In our study, occlusions also occurred, such as branches, leaves from lower vegetation, or other obstacles that partially obscured parts of the trunk. As a result, the automatic fitting process generated incomplete data, which could lead to an underestimation of the volume. Conversely, if the leaves were mistakenly counted as part of the trunk, the volume could be overestimated.

These issues frequently led to poorly fitted geometries and difficulties in accurately identifying the treetop. To address this, the study incorporated additional field measurements to improve the fitting process and reduce major errors in stem volume prediction. The findings demonstrate that combining TLS point clouds with simple field measurements can significantly enhance the accuracy of stem volume estimation compared to using TLS data alone [25].

In the study by Wang et al. [26], the number of trees that could be manually detected in terrestrial and airborne point clouds was assessed. The results showed that the denser the forest stand, the fewer stems could be detected. At the plot level (fixed plots of 32 m × 32 m), TLS with five scan positions captured approximately 97% of individual trees in low-density stands (about 700 stems/ha), 93% in medium-density stands (about 900 stems/ha), and 75% in high-density stands (about 2,200 stems/ha). Using UAV-LS with a point density of around 450 points/m², 87%, 69%, and 55% of the individual trees were detected low-, medium-, and high-density stand types, respectively. The study of Wang et al. [26] highlights the potential of a combined approach: using manually measured DBH values from TLS together with tree heights derived from UAV-LS proves to be particularly promising [26].

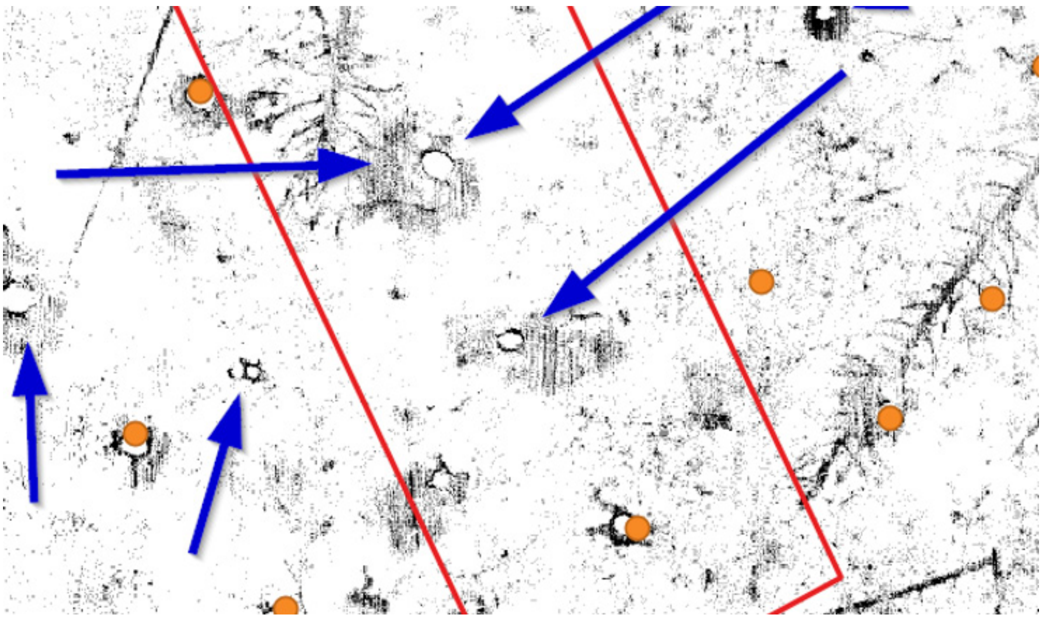

Fig. 7

Figure 7:
Example of missed tree stems in single tree detection

Abbildung 7:
Beispiel für fehlende Baumstämme in der Einzelbaumdetektion

Figure 7 illustrates a representative example from our study. While the yellow dots indicate the positions of detected individual trees from the UAV-LS data, the underlying point density map suggests that several stems were missed during the detection process.

Our study also revealed that individual tree segmentation based on laser scanning data (both TLS and UAV-LS) shows inaccuracies, despite the high level of detail in the data, particularly in very steep or densely vegetated areas. Segmenting individual trees from laser scanning data has long been a major challenge in forest remote sensing. When determining above-ground biomass based on laser scanning data, not only the volume of the trunk, but also the volume of the branches, is taken into account. While the estimation of stem biomass is relatively straightforward, capturing the tree crown using TLS is significantly more complex due to overlapping branches [27]. In our study, this led to several cases where two neighboring trees were erroneously segmented as a single tree, especially in the upper canopy layers captured with UAV-LS data (Figure 8).

Fig. 8

Figure 8: Incorrect individual tree segmentation due to overlapping branches

Abbildung 8: *Fehlerhafte Einzelbaum Segmentierung aufgrund überlappender Äste*

While numerous algorithms for tree segmentation are available, comparative studies remain scarce due to the difficulty of obtaining reliable reference data. The need to evaluate tree segmentation algorithms directly using benchmark datasets, rather than relying on indirect comparisons through forest metrics such as biomass, or the number and size distribution of trees, is emphasized in the literature [28].

In the study by Abegg et al. [29], it was found that volume estimates derived from point clouds are systematically biased—by around 25% for small trees and only a few percent for larger ones. In particular, small tree components with diameters under 7 cm cannot be estimated with sufficient accuracy. For small trees with a DBH of 12 cm, the volume of these components is overestimated by an average of 110%, with high variability. In contrast, for large trees (DBH ≥ 75 cm), the same components are underestimated by an average of 50% [29].

Given the benefits of integrating multiple remote sensing platforms, it is not surprising that various studies have already explored the combination of UAV, TLS, and airborne laser scanning (ALS) data. However, most of these approaches remain resource-intensive and often involve downsampling or aggregation, which leads to a reduction in point density or spatial resolution compared to the original capabilities of the sensors [12]. In this context, Calders et al. [12] raise a critical but still insufficiently addressed question: to what extent do such processing steps result in the loss of valuable structural information — and does this loss actually impact the accuracy or relevance of specific ecological applications?

Challenges in detecting lying deadwood

Detecting lying deadwood remains challenging, as overstory canopy, dense understory vegetation, and ground obstructions like rocks often interfere with reliable identification. Recent methods apply object-based image analysis or clustering techniques on point cloud data, but their effectiveness is typically limited to larger logs with DBH exceeding 25–30 cm [30].

Our study reached similar conclusions. The results showed that reference data collected using the line intersect method yielded nearly twice the amount of deadwood biomass compared to the automated drone-based analysis.

The line intersect method assumes that deadwood is randomly distributed across the sampling area, without directional bias. However, this assumption may not hold true in the Natural Forest Reserve Rohrach, where deadwood distribution could be influenced by slope processes, windthrow direction, or past disturbances. But this bias has been largely mitigated by the perpendicular orientation of the two transects within each plot.

Additionally, the UAV-LS based method may underestimate deadwood volume in dense canopy areas, where fallen trunks beneath the crown cover remain undetected by the aerial laser scan. These factors likely contributed to the lower deadwood estimates obtained from the UAV-based approach.

To determine whether the line intersect method may be unsuitable in this context—due to its assumption of a random distribution of logs—or whether the UAV-based approach systematically fails to detect a significant number of logs, a complete census of deadwood on a test plot would be required.

OUTLOOK AND LIMITATIONS OF THE STUDY

The findings of this study provide a valuable foundation for subsequent research. The collected data offer substantial potential for additional analyses and extended applications. At the same time, certain methodological and evaluative limitations must be acknowledged. This section therefore outlines the most relevant limitations of the present study and highlights potential directions for further analyses and future research.

This study compared three methods for determining above-ground biomass (field-based forest inventory, TLS, and UAV-LS), but the sample size varied. The field-based forest inventory used 44 sample areas, while TLS only considered 18 of the areas (due to inaccessible terrain). UAV-LS was performed across the entire area.

Moreover, the three methods were not applied in complete methodological isolation. Tree height, for instance, was not measured during the field inventory but subsequently derived from TLS data and then incorporated into the field dataset. This approach was chosen because field-based height measurements are prone to substantial inaccuracies, whereas TLS provides more reliable estimates. Field measurements are more sensitive to stand density, crown classes, and tree species than ALS and TLS measurements. Overall, field-based measurements tend to overestimate the height of tall trees, particularly the largest individuals. In dense stands, field-measured heights of smaller trees also exhibit considerable uncertainty [17]. Nevertheless, for a rigorous comparison of the three approaches, such cross-use of information should ideally be avoided.

In this study, only UAV-derived estimates were compared with the field-based line intersect method for lying deadwood. This comparison yielded markedly different results (see Discussion, Section 3). For the sake of completeness and to strengthen the overall analysis, it would also be valuable to derive deadwood estimates from the TLS data.
To estimate above-ground biomass from the UAV and TLS laser scanning data, QSM models were applied in this study. Nevertheless, numerous alternative approaches for biomass estimation from LiDAR data exist, and a comparison of these methods would be of considerable interest. The same consideration applies to deadwood assessment. In this study, a voxel-based approach was employed, although various other methods are also available.
Beyond QSM models and voxel-based techniques, allometric models, machine learning approaches, and advanced deep learning frameworks such as 3D-CNNs could be explored, either individually or in combination, to further improve biomass and deadwood estimation.

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