

Evaluating the reliability of the 1-meter resolution meta-estimated global canopy height map for estimating forest structural metrics in Alpine environment

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ABSTRACT

Monitoring forests globally through the assessment of structural characteristics is indispensable in times of increasing disturbances and biodiversity loss. The recent development of a 1-meter resolution Global Canopy Height Map by Meta and the World Resources Institute (Meta/WRI CHM) offers new opportunities for large-scale forest structure analysis. However, its reliability for estimating key forest structural metrics in selected forest sites of the Italian Alps remains largely untested. In this study, we compared estimates of canopy cover, mean and maximum canopy height, tree count, and crown size computed from the Meta/WRI CHM with the corresponding metrics computed from airborne laser scanning (ALS)-based CHMs across five forested sites in Alpine ecosystems representing diverse forest structures, species compositions, and management practices. Our results show that the Meta/WRI CHM provides reliable estimates of canopy cover ($R^2 = 0.82\text{--}0.92$, RMSE = 8%–15%) and, to some extent, mean canopy height ($R^2 = 0.69\text{--}0.85$, RMSE = 2.2–2.9 m). However, it substantially underestimates maximum canopy height and fails to reliably estimate tree count, positions, and crown size, overestimating the number of trees by 200–750 per hectare. In addition, the quality of the evaluated metrics estimates varied with respect to topographic gradients (i.e., slope, aspect, and altitude). Our findings define clear application boundaries for the Meta/WRI CHM in Alpine forest environments: while the product can support stand-level estimates of canopy cover and mean canopy height, it remains unsuitable for estimating maximum canopy height and individual-tree-level metrics such as tree count, tree position, and crown size. Future efforts should focus on refining global CHMs to improve accuracy and expand their applicability for forest monitoring.

1. Introduction

Forests occupy roughly 30% of the Earth's land area and are essential to the livelihoods of about 1.6 billion people, supplying them with food, medicine, fuel, and other vital resources (Jenkins and Schaap,

2018). Forest structure, the three-dimensional arrangement of vegetation, creates a complex environment that strongly influences forests' ability to sequester carbon (Rödig et al., 2018; S.M. Fischer et al., 2024) and underpins overall forest biodiversity (Torresani et al., 2020,

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2025; Hakkenberg and Goetz, 2021). In addition, forests with well-maintained structures are more resilient to disturbances such as pests (Torresani and Tognetti, 2024; De Groot et al., 2019), diseases, and extreme weather events (Zeng et al., 2010; Torresani et al., 2024a), which are becoming increasingly frequent with climate change (Altman et al., 2024). Forest structure also regulates other ecosystem services, including water regulation (Caputo et al., 2016), nutrient cycling (Villega et al., 2006), and recreational opportunities (Kim et al., 2020; Sacher et al., 2022). This places detailed global mapping of forest structure among the highest-priority variables to be monitored from space.

Measuring forest structure and variables, such as tree height, canopy cover, crown size, and tree density, has traditionally relied on extensive fieldwork, which is time-consuming, costly, and especially challenging in large or remote areas. Remote sensing technologies, especially lidar (Light Detection and Ranging), including airborne laser scanning (ALS), provide a powerful alternative by delivering accurate, large-scale data with continuous coverage that is not feasible with field-based measurements (Kacic et al., 2025). A key product of ALS is the Canopy Height Model (CHM), which is widely used to estimate critical forest metrics (F.J. Fischer et al., 2024), including biomass (Puliti et al., 2020), carbon storage, and forest productivity (Socha et al., 2020). CHMs are also essential for biodiversity assessments (Torresani et al., 2024b), habitat modeling (Shanley et al., 2021), identifying canopy gaps (Dalagnol et al., 2021), monitoring forest health (Meng et al., 2022), and assessing the impacts of disturbances such as logging or natural disasters (Torresani et al., 2024a).

Having access to a global CHM at a fine resolution, similar to that provided by ALS, would represent a major breakthrough for forestry and environmental monitoring worldwide. The ability to analyze forest variables at such a detailed level on a global scale would greatly enhance forest management practices and provide critical information for addressing pressing environmental challenges such as climate change and habitat loss. However, the use of ALS for this purpose is hindered by the cost of data acquisition, and large-scale coverage is restricted to regions such as Europe and the United States (Moudry et al., 2023; Stoker and Miller, 2022).

Recent developments in spaceborne lidar missions, particularly the Global Ecosystem Dynamics Investigation (GEDI), offer a means to overcome the limited spatial and temporal coverage of ALS data (Dubayah et al., 2022; Hakkenberg et al., 2023; Pracna et al., 2025; Torresani et al., 2026). However, GEDI produces discrete footprints with limited sampling density rather than continuous, wall-to-wall CHMs. Furthermore, the accuracy of GEDI data can be affected by atmospheric conditions and surface characteristics, and extensive filtering processes are required to generate high-quality outputs reduce the volume of usable data (Moudry et al., 2024b). As a result, the spatial resolution of global CHMs is relatively coarse, typically around 1 km or more (Burns et al., 2024), making them suitable for large-scale studies but less optimal for fine-scale applications.

The absence of a high-resolution, global CHM has led researchers to integrate spaceborne lidar with other satellite datasets in order to generate continuous CHMs at resolutions of tens of meters. For example, Potapov et al. (2021) and Lang et al. (2022, 2023) utilized GEDI together with Landsat and Sentinel-2, respectively, to estimate global canopy height. More recently, Meta and the World Resources Institute utilized Maxar and Vivid2 imagery (i.e., mosaicked imagery from WorldView-2, WorldView-3, and Quickbird II) to develop a global CHM at an unprecedented 1 m resolution (Tolan et al., 2024) (freely available at this link). This fine resolution dataset is particularly valuable for detailed forest resource mapping and analysis. Notably, a few recent studies validated the three global CHMs mentioned above, and highlighted their accuracy limitations (Moudry et al., 2026). However, targeted evaluations of the accuracy and reliability of the latest 1-meter resolution Meta/WRI CHM dataset under complex Alpine forest conditions remain limited.

Therefore, this study aims to provide a site-specific evaluation of the Meta/WRI 1-meter Global Canopy Height Map (Tolan et al., 2024) by comparing it with ALS-derived CHMs in Alpine forests of northern Italy. The study deliberately focuses on five Alpine forest regions that are well known in terms of forest management, species composition, and recent disturbance history, enabling a controlled assessment of product performance in structurally complex mountainous environments. The specific objectives are to: (1) assess key forest canopy metrics, including canopy cover, canopy height, tree count, and crown size, within these Alpine sites; and (2) analyze how topographic gradients (slope, aspect, and altitude) influence the agreement between the Meta/WRI CHM and ALS-derived reference data.

2. Materials and methods

2.1. Study area

We evaluated Meta/WRI's fine resolution CHM in five forest areas in the Province of Trento, Italian Alps: Avio, Dro, Ledro, Rumo, and Vermiglio (Fig. 1). Although geographically limited to the Italian Alps, these sites span wide gradients in elevation, slope, forest management, and species composition that are characteristic of many Alpine forest environments. The objective was to evaluate product performance under structurally complex mountainous conditions typical of different Alpine regions, rather than to claim full representativeness across all Alpine forests or at national and continental scales. Each area covers approximately 1600 hectares. For validation, we randomly selected 400 one-hectare subplots in each area, each measuring 100 × 100 m, restricted to areas classified as forest using the official forest mask provided by the local forestry service and available here <https://siat.provincia.tn.it/geonetwork/srv/ita/catalog.search#/home>. Random sampling was used to avoid subjective selection of homogeneous stands and to evaluate the Meta/WRI CHM under realistic, heterogeneous Alpine forest conditions, rather than to isolate species or management specific effects.

The forest types in these areas range from species that thrive in warmer conditions, such as Manna ash (*Fraxinus ornus*), Hop-hornbeam (*Ostrya carpinifolia*), and Scots pine (*Pinus sylvestris*), to species adapted to moderate climates like European beech (*Fagus sylvatica*), and those suited to cold environments, including Norway spruce (*Picea abies*), European larch (*Larix decidua*), and Swiss stone pine (*Pinus cembra*). The characteristics of forest management and species diversity within these areas were estimated using data provided by the local forestry service. These data include detailed information on forest types and management practices (e.g., high forest, coppice, mixed management) across the study areas and are freely available for download at <https://siat.provincia.tn.it/geonetwork/srv/ita/catalog.search#/home> and summarized in Table 1. These data were used to describe the ecological and management context of the study areas and to document the range of forest conditions included in the validation.

The study area of Avio is located on the north side of the Avio village, ranging from approximately 200 m to 1500 m above sea level. The forest is predominantly coppice, with smaller proportion of high forest (forests primarily composed of trees grown from seed rather than vegetative regeneration) and mixed management. Forest types are diverse: manna ash and hop-hornbeam (*Fraxinus ornus*, *Ostrya carpinifolia*) and beech (*Fagus sylvatica*) being the most common, followed by pine (*Pinus sylvestris*), larch (*Larix decidua*), Norway spruce (*Picea abies*), silver fir (*Abies alba*), and transitional forest formations present in minor proportions (Table 1).

The study area of Dro is located on the east side of the village, on the slopes of the Stivo mountain peak ranging from around 600 m to 1800 m above sea level. The forest exhibits a balanced mix of management types, including coppice, high forest, and mixed management. The forest is dominated by Beech (*Fagus sylvatica*), followed by manna ash and hop-hornbeam (*Fraxinus ornus*, *Ostrya carpinifolia*)

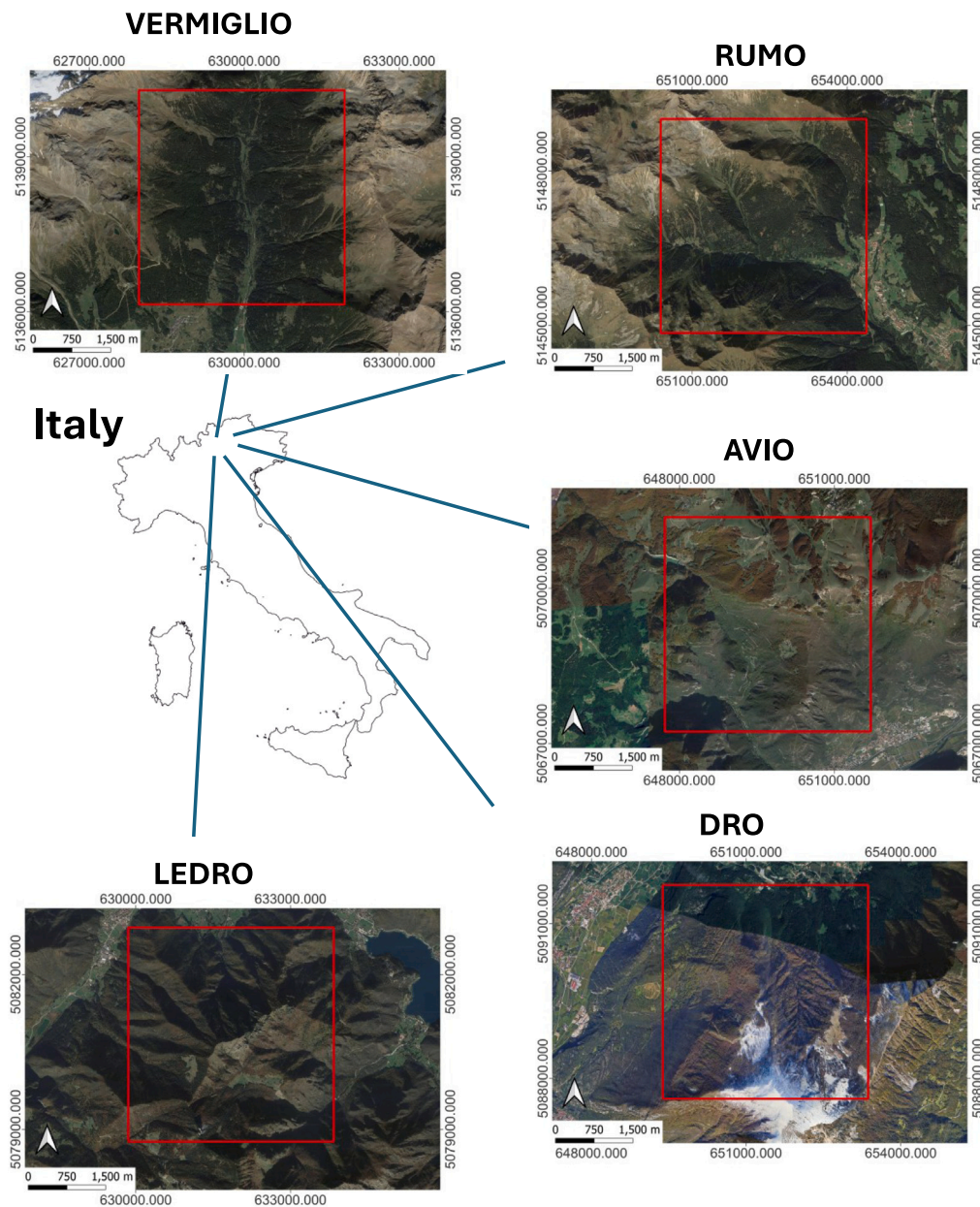


Fig. 1. Locations of the five study areas. Coordinates are in UTM 32 N (EPSG:32632).

and larch (*Larix decidua*) as moderately abundant species, with Norway spruce (*Picea abies*) and Holm oak (*Quercus ilex*) occurring only in small amounts (Table 1).

The study area of Ledro is located on the south side of the village, on the slopes of the Corno mountain peak ranging from around 700 m to 1700 m above sea level. The forest is predominantly high forest, with mixed management making up a smaller portion and coppice representing only a minor fraction. The forest types are diverse dominated by Norway spruce (*Picea abies*), followed by Beech (*Fagus sylvatica*), Hop hornbeam–Oak, and Silver fir (*Abies alba*) as moderately abundant species. Pine (*Pinus sylvestris*) occurs less frequently, and Mountain pine (*Pinus mugo*) is present only in small amounts (Table 1).

The study area of Rumo is located at the northwest side of the village, covering both “Val” and “Lavazzè” valley, it ranges between around 1000 m and 2600 m above sea level. The forest is almost entirely high forest, with only a small portion under coppice and mixed management. Norway spruce forest (*Picea abies*) is the dominant type,

accompanied by Green alder formations, Larch forest (*Larix decidua*), and Silver fir forest (*Abies alba*), while transitional formations are minimally represented (Table 1).

The study area of Vermiglio is located at the foothill of the Boai peak, it ranges from 1300 m to 2500 m above sea level. The forest is almost completely managed as high forest with a small proportion of coppice. Norway spruce forest (*Picea abies*) dominates, accompanied by substantial Larch forest (*Larix decidua*), while Green alder formations and Swiss stone pine forest (*Pinus cembra*) are minimally represented (Table 1).

This combination of contrasting low- and high-elevation forests, different management systems, varying canopy densities, and mixed broadleaved-to-conifer-dominated compositions makes these areas suitable for evaluating the performance of the Meta/WRI CHM dataset across a broad spectrum of Alpine ecological and structural conditions.

Table 1

Summary of forest management and forest types by study area, based on a synthesis of local forest type classifications (Provincia Autonoma di Trento, 2025).

Study area	Forest management type	%	Forest type	%
Rumo	High forest	80	Norway spruce forest	67
	Mixed management	5	Green alder formations	14
	Coppice	15	Larch forest	9
			Silver fir forest	8
			Transitional formations	2
Vermiglio	High forest	95	Norway spruce forest	56
	Mixed management	0	Larch forest	38
	Coppice	5	Green alder formations	4
			Swiss stone pine forest	2
Ledro	High forest	70	Norway spruce forest	52
	Mixed management	20	Beech forest	17
	Coppice	10	Hop-hornbeam-Oak forest	10
			Silver fir forest	10
			Pine forest	9
			Mountain pine forest	2
Dro	High forest	30	Beech forest	54
	Mixed management	25	Manna ash and hop-hornbeam forest	19
	Coppice	45	Larch forest	15
			Norway spruce forest	8
			Holm oak forest	4
Avio	High forest	10	Manna ash and hop-hornbeam forest	47
	Mixed management	15	Beech forest	42
	Coppice	75	Pine forest	4
			Larch forest	3
			Norway spruce forest	2
			Silver fir forest	1
			Transitional formations	1

2.2. Remote sensing data

2.2.1. ALS lidar dataset

For a vertical accuracy assessment, highly accurate reference data is necessary, ideally at least three times more accurate than the dataset being evaluated (Maune, 2007). As mentioned above, CHM accuracy typically required for forest applications is around 2 m (Fassnacht et al., 2024) which is an ideal that the Meta/WRI CHM dataset likely does not meet (Moudrý et al., 2024a). However, assuming this target is appropriate, reference data should have an accuracy of at least 0.7 m, which ALS data easily satisfy (Hollaus et al., 2006). Therefore, in this study, we used CHMs generated from the ALS campaign conducted between 2014 and 2018 across the entire Province of Trento (see lidar characteristics in Table 1 of Supplementary material).

The dataset, available as point cloud data in .laz format, is freely accessible and can be downloaded from the following link: <https://siat.provincia.tn.it/stem/>. The data were collected using the ALT M Gemini laser-scanning system (ALTM 3100 EA and LMS Q780), with an average point density of 10 points per square meter (pts/m²). To create the reference CHM, ALS point clouds (already classified) were processed in R using the `lidR` package following a standard workflow. A 1 m DTM was interpolated from ground points using `rasterize_terrain()` with the `tin()` algorithm, and point heights were normalized with `normalize_height()`. Points with normalized heights below 0 m or above 40 m were removed, and the final 1 m reference CHM was generated using `rasterize_canopy()` with the `p2r()` point-to-raster algorithm.

We note that ALS-derived CHMs are not error-free and are subject to uncertainty related to point density, ground-point classification, terrain interpolation, and rasterization choices; however, when processed using established workflows, such as the one adopted here, and high-density data, they provide a robust reference for comparative evaluation.

2.2.2. Meta/WRI CHM dataset

The Meta/WRI CHM dataset, with a spatial resolution of 1 m, was downloaded from the GEE platform at this link [\[catalog.org/projects/meta_trees/#dataset-citation\]\(https://catalog.org/projects/meta_trees/#dataset-citation\) using the same coordinate reference system as the ALS data. The CHM dataset is predicted from Maxar satellite imagery \(mosaicing together imagery from multiple instruments such as WorldView-2, WorldView-3 and Quickbird II\). The dataset analyzes the highest-quality available satellite imagery from the years 2009 through 2020, with eighty percent of the data produced using imagery from 2018 to 2020 \(Meta AI Sustainability Team, 2024\). The process involved training a model on ALS data from various sites in the USA and in Brazil using self-supervised learning to enhance the model's ability to generalize across different landscapes. The model was then refined using GEDI data, which provided a broader context and helped correct potential systematic errors in canopy height estimation.](https://gee-community-</p>
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2.3. Forest structural metrics and derivation procedures

In this study, we conducted a comparative evaluation of the Meta/WRI CHM by deriving a set of forest structural metrics and comparing them with the same metrics computed from the reference ALS-derived CHM. All metrics were calculated using identical definitions, thresholds, and spatial support for both datasets to ensure methodological consistency. Before metric extraction, the ALS-derived and Meta/WRI CHMs were harmonized to ensure spatial comparability. Both rasters were used in the same coordinate reference system and at 1 m spatial resolution, and the same 100 × 100 m plot boundaries were applied to both datasets.

The goal was to assess the reliability and accuracy of the Meta/WRI CHM across diverse forest conditions and management practices. The metrics were tested in each of the random plots for each study area and include:

- **Maximum Canopy Height (max CHM):** the maximum height of the CHM, which reflects the tallest trees.
- **Mean Canopy Height (mean CHM):** the average height of the CHM within each 100 × 100 m plot, calculated as the arithmetic mean of all valid CHM pixels. No height threshold was applied for this metric; therefore, low or zero-height pixels were retained, and only no-data pixels were excluded.

- **Canopy Cover::** the ratio between the number of pixels with CHM > 2 m and the total number of pixels:

$$\text{Canopy cover} = \frac{px_{2m}}{px_{tot}} \times 100 \quad (1)$$

where:

px_{2m} = number of pixels with a CHM > 2 m
 px_{tot} = total number of pixels

- **Tree Count:** The number of individual trees estimated using a tree top detection algorithm based on the CHM (using the `lidR` R package) involving the following steps:

- *Variable Window Size Calculation:* the window size for tree top detection was dynamically predicted based on the mean canopy height (`mean_chm`) of each plot. The window size was determined using the formula:

$$\text{window size} = (\text{mean_chm} \times 0.1) + 3$$

This ensures that the detection process is adapted to the varying tree heights across different plots.

- *Tree Top Detection:* a local maximum filter (`lmf`) was applied to detect potential tree tops in the CHM within the specified window size.
- *Tree Segmentation:* The `dalponte2016` algorithm (Dalponte and Coomes, 2016) of the `lidR` R package was used to segment individual trees based on the detected tree tops and the CHM data, allowing for the estimation of tree count.

- **Crown Size:** The area of individual tree crowns, expressed in square meters (m^2), was estimated following the segmentation process. Crown size was determined by counting the number of pixels associated with each tree after segmentation. Given the 1 m^2 resolution, the crown size of each tree corresponded directly to the number of pixels.

2.4. Statistical analysis

To evaluate the accuracy of the Meta/WRI CHM against the ALS-derived reference CHM across the five study areas, several statistical analyses were conducted. First, linear regression analysis was performed to describe the relationship between ALS-derived and Meta/WRI-derived estimates for key canopy metrics (canopy cover, mean CHM, maximum CHM, and tree count). The proportion of variance in the ALS-derived metrics explained by the corresponding Meta/WRI-derived metrics was quantified using R^2 , while RMSE was calculated to quantify the overall magnitude of the differences between the two datasets. In addition, Bland Altman analysis was employed to assess agreement between the ALS and Meta/WRI CHM datasets. This method involved visualizing the differences in metric values between the two sources against their averages for each plot, providing insights into systematic errors and the limits of agreement, defined as the mean difference ± 1.96 times the standard deviation of the differences (Bland and Altman, 1986). A distribution analysis was also carried out by comparing the frequency distributions of the key canopy metrics between the ALS and Meta/WRI CHM datasets. The statistical significance of the differences between distributions was determined using p-values from a t-test.

Subsequently, we conducted a combined analysis of all plots across the study areas, rather than analyzing them separately for each site. This involved linear regression analysis, including RMSE calculations, to evaluate how the relationships between the structural variables vary with different topographic factors such as slope, aspect, and altitude. They were derived from the 1-m ALS-based DTM using the `terrain()` function of the `raster` R package. For each 100 $\times$ 100 m plot, mean altitude, mean slope, and mean aspect were then extracted by

overlaying the plot polygons on the corresponding rasters. These plot-level topographic variables were used to group plots into topographic classes and to assess variation in the agreement between Meta/WRI- and ALS-derived forest structural metrics. This approach allowed us to assess the influence of topography on the performance of the Meta/WRI CHM across diverse environmental conditions. We also conducted a comparative analysis of tree counts and crown sizes by examining the p-values from t-tests, which compared the number of trees and crown sizes estimated by the Meta/WRI CHM and ALS CHM across different canopy cover thresholds (i.e., plots grouped by canopy cover percentage classes, such as 10%, 20%, 30%, etc.).

To assess potential spatial autocorrelation in our sampling design, we applied Moran's I to the centroid coordinates of plots in each study area and tested whether structural variables at neighboring plots exhibited significant spatial dependence; no significant spatial dependence was detected. Additionally, we examined the heteroscedasticity of the relationships between ALS-derived and Meta-derived canopy metrics using the Breusch–Pagan test as diagnostic check to assess whether residual variance varied across fitted values. This test was conducted separately for each study area and for each key structural variable (mean CHM, max CHM, tree count, and canopy cover).

3. Results

3.1. Canopy cover and height

Canopy cover and mean canopy height from the Meta/WRI CHM showed strong linear relationships with the corresponding values from the ALS CHM across all study areas, with R^2 values ranging from 0.82 to 0.92 and 0.69 to 0.85, respectively (Fig. 2). The distribution comparisons provide an initial indication of systematic differences between the datasets, including underestimation of high canopy cover values and a tendency toward lower mean canopy height values in the Meta/WRI CHM (Fig. 3). These patterns are further quantified by the Bland–Altman analysis described below. The distribution of canopy cover values showed clear differences between the ALS and Meta/WRI CHM datasets across the five study areas, particularly in regions with high canopy cover, which tended to be underestimated. For mean canopy height, the Meta/WRI CHM tended to report smaller values across all study areas. Maximum canopy height showed weaker and more variable relationships, with R^2 values ranging from 0.12 to 0.73 across study areas, and the Meta/WRI CHM dataset had difficulty reliably capturing maximum canopy heights, particularly for taller canopies above 30 m, where it tended to underestimate height (Fig. 3). This is illustrated in canopy height profiles along an example transect, which show that the Meta/WRI CHM underestimates canopy height and has a reduced ability to capture variations in canopy height (Fig. 4).

The overall mean difference (bias) between predicted (Meta/WRI CHM) and reference (ALS CHM) values for canopy cover was close to zero; however, the direction and magnitude of bias varied with respect to estimated canopy cover. Across all study areas, the Bland–Altman plots indicated that the Meta/WRI overestimates canopy cover when cover is low and underestimates it when cover is high, with the magnitude of these differences depending on the study area (Fig. 5). Mean canopy height tended to be slightly underestimated, with differences up to about 6 m, but the differences increased notably at greater canopy heights. Maximum canopy height showed considerably larger differences than mean canopy height. The Bland–Altman plots revealed a strong, consistent negative bias, with mean differences ranging between 5–10 m depending on the study area (Fig. 5), indicating that the Meta/WRI CHM systematically underestimated maximum canopy heights (Fig. 4).

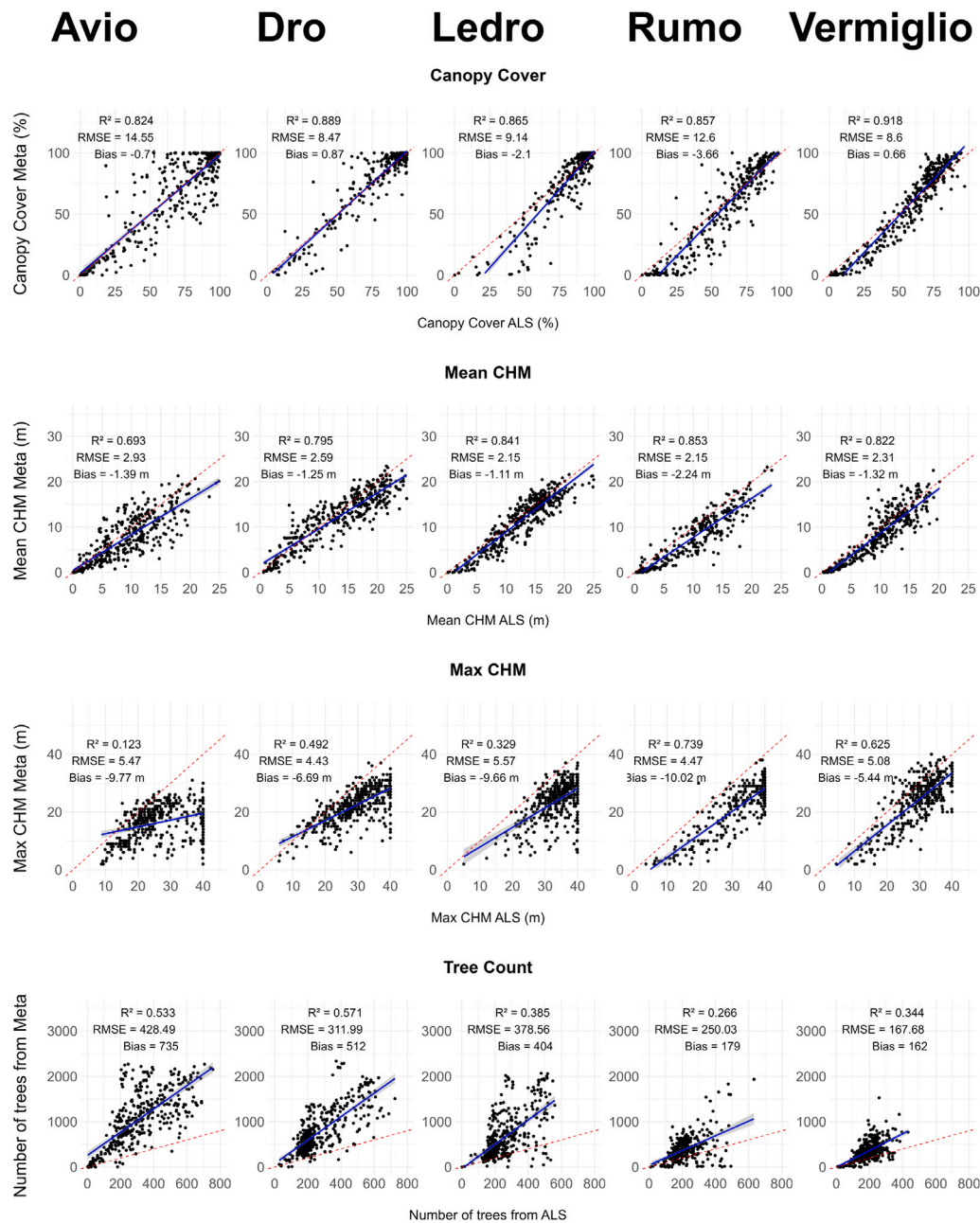


Fig. 2. Linear regressions between the ALS and Meta/WRI CHM datasets for given metrics (canopy cover, max CHM, mean CHM, and tree count) across the five study areas (Avio, Dro, Ledro, Rumo, Vermiglio). Analyses were conducted on a sample of 400 plots per study area.

3.2. Number of trees and crown size

Number of trees derived from the Meta/WRI CHM showed weak relationships with the corresponding values from the ALS CHM across all study areas, with R^2 values ranging from 0.26 to 0.57 (Fig. 2). The Meta/WRI CHM dataset has consistently overestimated the number of trees relative to ALS, with average differences ranging from 200 to 750 trees per hectare, depending on the study area. Moreover, the degree of overestimation increased with higher tree counts (Fig. 5). Indeed, for most canopy cover classes (except for the 10% and 20% canopy cover class), we observed significant differences in the number of trees counted by ALS and Meta/WRI (Figure 1S of Supplementary Material). In addition, the locations of identified trees differed considerably between the ALS CHM and the Meta/WRI CHM (Fig. 6), indicating that the Meta/WRI CHM lacks the spatial accuracy required for reliable individual-tree detection. This is also evident from the analysis

of crown sizes. The Meta/WRI CHM struggled to accurately estimate crown size compared to ALS, with this limitation being particularly pronounced in areas with greater canopy cover (Figure 2S of Supplementary Material). Overall, the Meta/WRI CHM proved unsuitable for deriving meaningful crown size estimates due to its reduced ability to capture variations in canopy height (Fig. 4).

3.3. Effect of slope, altitude and aspect

In this case, the analysis has been performed on all the study areas together, and not divided by the single study area. Canopy cover and mean CHM showed stronger linear relationships (higher R^2 values) with the reference data than maximum canopy height and tree count across all environmental conditions (Fig. 7). The accuracy of canopy cover, validated using RMSE, was primarily influenced by altitude, likely because the relatively lower canopy cover at higher elevations

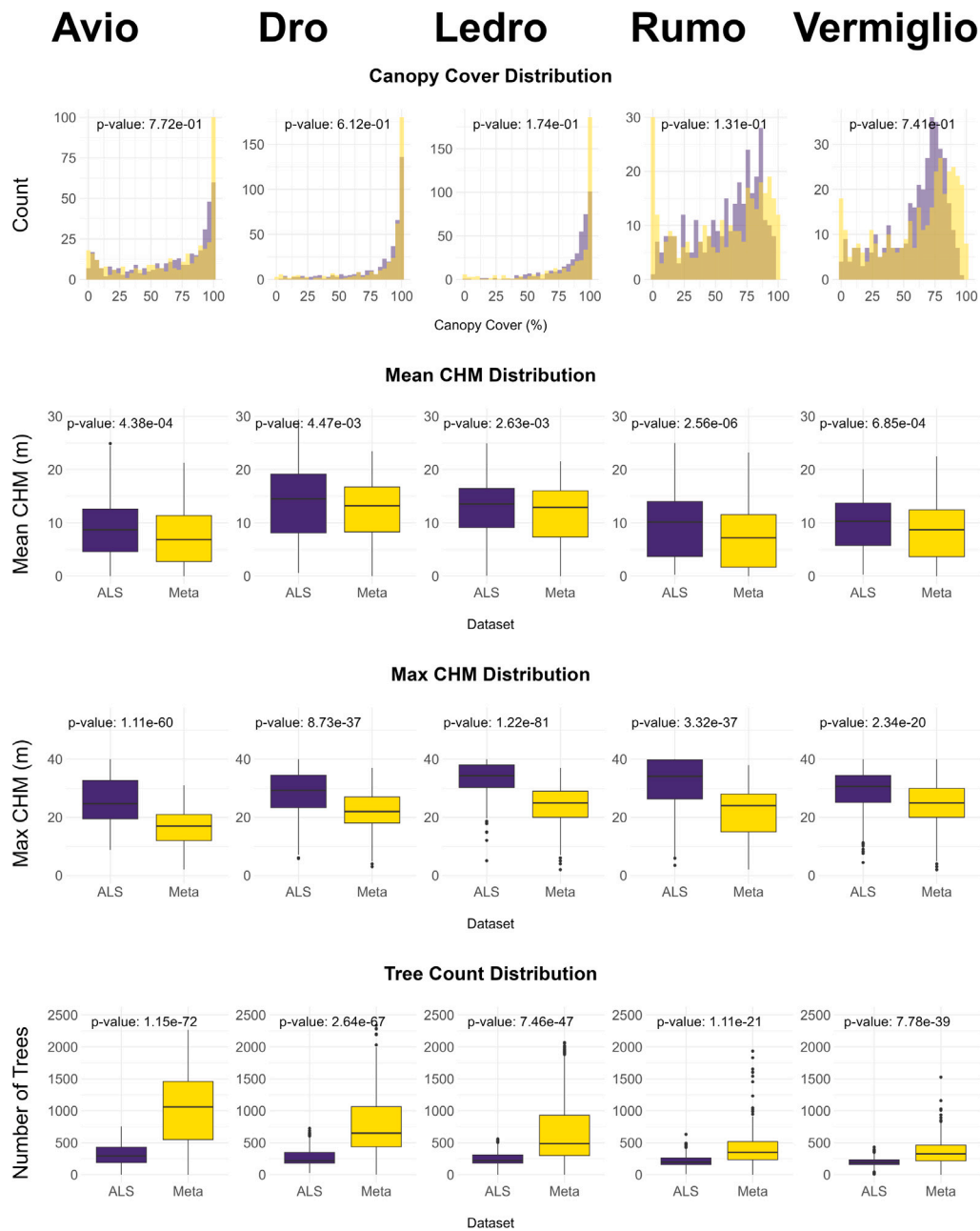


Fig. 3. Distribution comparisons between the ALS and Meta/WRI CHM datasets for the key canopy metrics (canopy cover, max CHM, mean CHM, and tree count) across the five study areas (Avio, Dro, Ledro, Rumo, and Vermiglio). Each row represents the distribution of a specific canopy metric, while the columns correspond to the different study areas. Statistically significant differences between the ALS and Meta/WRI datasets, indicated by p-values derived from a t-test, provide insights into the level of agreement or discrepancy in estimating forest structure metrics between the two methods.

is easier to model, and to a lesser extent by slope and aspect. The accuracy of Mean CHM showed minimal variation in accuracy across all environmental conditions, highlighting its consistency across diverse terrains. The accuracy of maximum CHM was only slightly affected by slope and altitude but showed large variations across different slope aspects. In contrast, the accuracy of tree count estimates was minimally influenced by aspect but declined considerably with increasing slope and decreasing altitude, likely due to higher forest density in lower elevations (Fig. 7). In addition to the absolute RMSE, we calculated the relative RMSE (rRMSE) to facilitate comparison of error magnitude across sites and environmental gradients with different mean reference values. The rRMSE was calculated as RMSE divided by the mean ALS-derived reference value within each bin and expressed as a percentage. These results are reported in the Supplementary Material.

4. Discussion

In this study, we evaluated the accuracy of the Meta/WRI CHM across diverse forest types, terrain conditions, and ecological and management contexts in the Italian Alps, assessing its reliability for mapping key aspects of forest structure, including canopy cover, canopy height, tree count, and crown size. The Meta/WRI CHM achieved R^2 values of 0.82–0.92 and RMSE values of 8%–15% for canopy cover (Fig. 2), indicating its suitability for canopy cover mapping. Note, however, that this contrasts with a recent study by Dong et al. (2025), which showed that global CHMs tend to exhibit notable omission and commission errors in canopy cover estimates in urban environments. Mean canopy height estimates were also reliable, with R^2 values of 0.69–0.85 and RMSE values of 2.15–2.93 m, approaching the 2 m accuracy

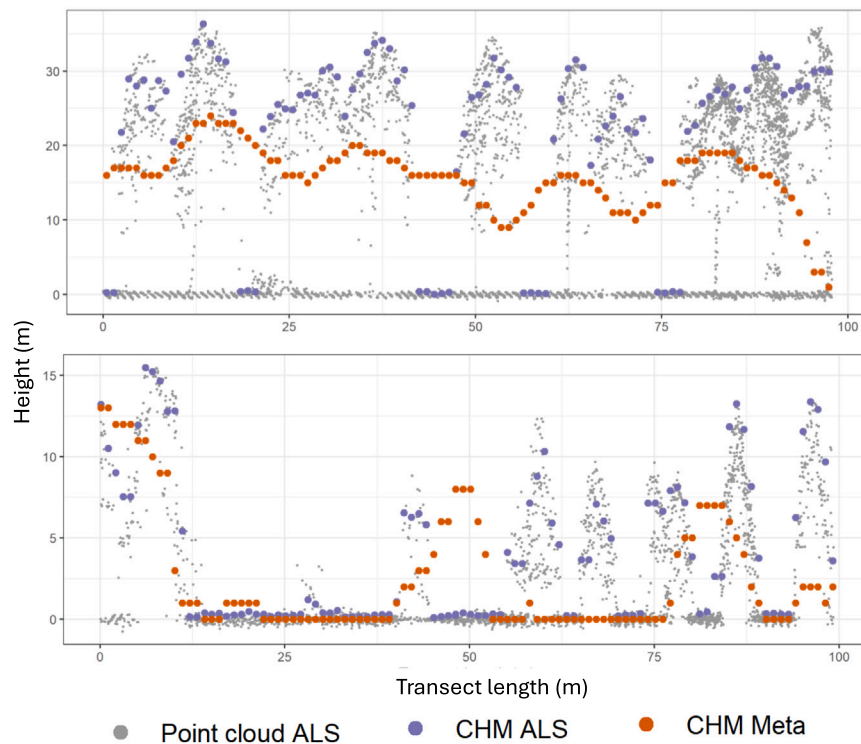


Fig. 4. Side view of the central transect of the example plot highlighted in Fig. 6, illustrating the ALS point cloud (gray dots), the ALS CHM (blue dots), and the Meta/WRI CHM (red dots). This transect was selected as an illustrative example and was not chosen through a best- or worst-agreement criterion. The visualization highlights differences in canopy height representation between the datasets, particularly in estimating the extremes of canopy structure.

typically required for forest applications (see review by Fassnacht et al. (2024)). However, the Meta/WRI CHM tended to underestimate both mean canopy height and canopy cover in areas of dense canopy cover (Fig. 3). For maximum canopy heights (which enables direct pixel-level comparison) the Meta/WRI CHM exhibited lower R^2 values, indicating challenges in accurately estimating the height of the tallest canopies (Fig. 4). The discrepancy between the relatively accurate representation of mean canopy height and less accurate maximum canopy height, is consistent with a recent findings of Besic et al. (2025), who demonstrated that different predicted CHM models capture different aspects of canopy height. Finally, Meta/WRI CHM tended to considerably overestimate tree numbers and struggled to accurately estimate tree positions (Fig. 6). As the number of trees increased, the error also grew (Fig. 2). Overall, in the evaluated Alpine environments the Meta/WRI CHM is unsuitable for deriving reliable tree number estimates due to its limited ability to capture variations in canopy height and should not be used for this purpose (Fig. 4). These discrepancies might be interpreted as the inherent characteristics of the Meta/WRI product itself, including model and sensor dependent limitations related to optical-image-based canopy height prediction, smoothing of local canopy-height extremes, signal saturation or shadowing in dense and tall canopies, and possible limitations in the representation of European mountain forests in the training and calibration data. These product-level limitations are consistent with the systematic underestimation of maximum canopy height and with the reduced ability of the Meta/WRI CHM to reproduce fine-scale canopy-height variability. Of course, residual uncertainty may also arise from the design of the present comparison, including the temporal offset between ALS and Meta/WRI acquisitions, steep Alpine terrain, possible residual co-registration differences between raster products, and the aggregation of 1-m CHM pixels to 100×100 m plot-level metrics (discussed in the limitation of the study).

Performance variations driven by topographic gradients differed among the evaluated metrics. Mean CHM maintained consistent accuracy, demonstrating robustness across varied terrain conditions. Similarly, maximum CHM showed relatively little sensitivity to slope and altitude, yet exhibited substantial variation across different slope aspects. In contrast, the accuracy of canopy cover and tree count was strongly influenced by terrain conditions, particularly altitude, with accuracy decreasing at lower elevations. This is likely due to the relatively greater forest stand height and heterogeneity at lower elevations, which are the primary factors affecting the accuracy of global canopy height maps (Chen et al., 2025; Dong et al., 2025). However, as shown in Fig. 6, significant discrepancies in tree count estimates persist even in low-density forests.

While CHMs derived from ALS lidar data are widely used to estimate canopy cover and height, and tree locations, they represent only a subset of the information available in ALS point clouds (Gaulton and Malthus, 2010). The full potential of ALS lies in its ability to estimate a wide range of forest attributes, including understory structure (Jarron et al., 2020; Moudry et al., 2023), individual tree segmentation (Qin et al., 2022), and vertical stratification of vegetation (Torresani et al., 2020), which are crucial for more comprehensive analyses of forest ecosystems. Global CHM, such as Meta/WRI dataset, still represents a substantial step forward. Although it may not predict all forest attributes with complete accuracy, it provides an approximate estimate of some forest metric, such as canopy cover and mean height, which are particularly valuable in remote and inaccessible areas where ground-based measurements are challenging or impossible (e.g. Gatti et al. (2025)). Nevertheless, there remains a need for improved versions to enhance accuracy and broaden the range of forest attributes that can be reliably estimated from global CHMs.

Our finding that the Meta/WRI CHM systematically underestimates canopy height is consistent with previous evaluations of global canopy height products (Moudry et al., 2024a; Chen et al., 2025). We acknowledge that the ALS data (2014–2018) and the Meta/WRI CHM, primarily

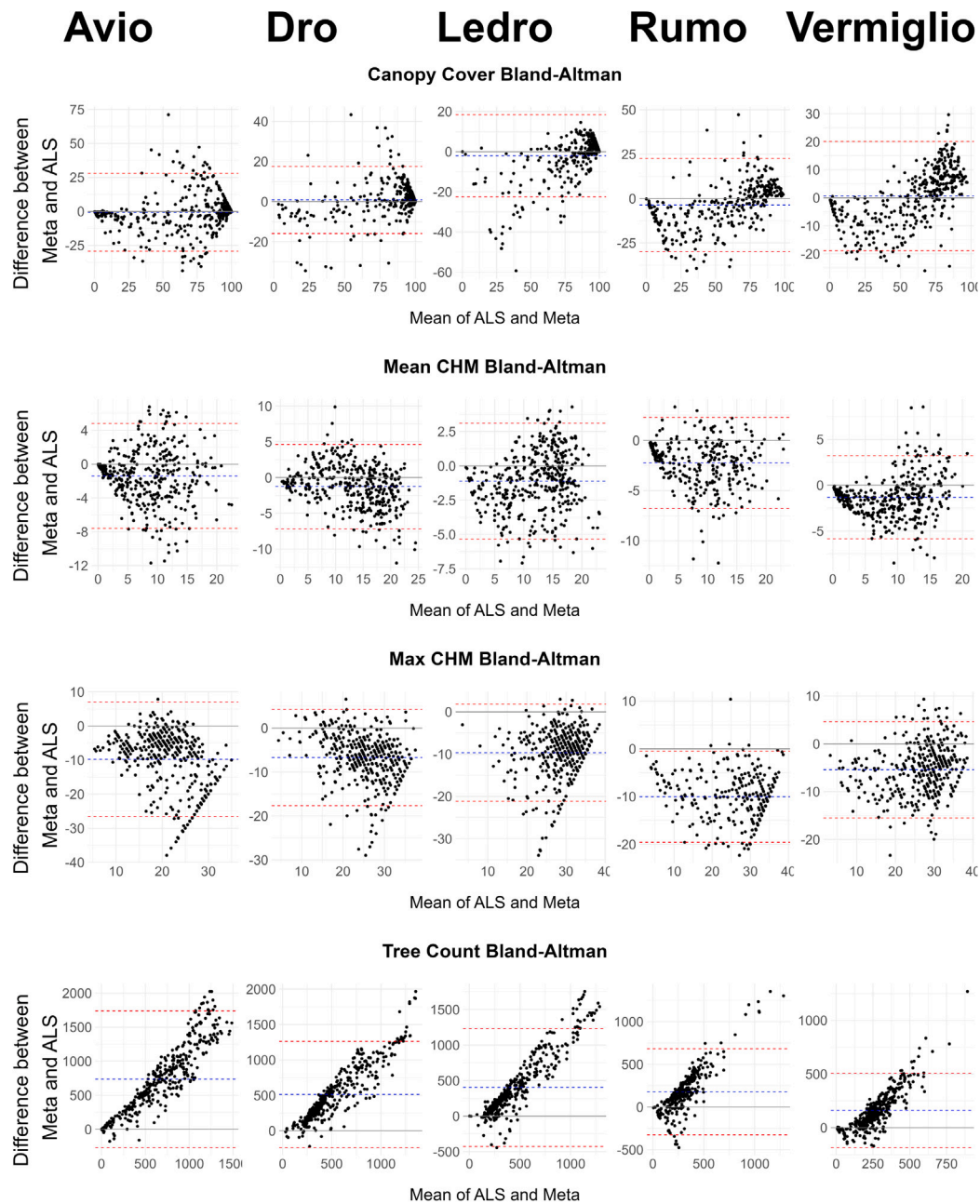


Fig. 5. Bland-Altman plots showing the agreement between Meta/WRI and ALS CHM estimates for four canopy metrics across the five study areas. The red dashed line represents the mean difference, and blue dashed lines indicate the limits of agreement (mean difference $\pm 1.96 \times$ standard deviation), within which 95% of the differences are expected to fall (Bland and Altman, 1986).

representing conditions from 2018–2020, are not temporally coincident, which represents a potential source of uncertainty. However, the study areas were deliberately selected based on our detailed, long-term knowledge of local forest dynamics and are regularly monitored by local forestry services. We can therefore state that no major disturbances, such as harvesting, windthrow, fire, or large-scale dieback, occurred between the ALS acquisition period and the time window represented by the Meta/WRI CHM. Gradual height growth is also unlikely to explain the observed bias. In Alpine forests, especially at mid to high elevations, structural change over short time intervals is generally limited. Recent studies have shown that vegetation height changes over decadal time spans in mountain forests are substantially smaller than the typical errors associated with global canopy height models (Moudrý et al., 2026). In addition, *Pinus cembra* height growth in the subalpine Austrian Alps has been shown to decrease with elevation, reflecting the

shorter growing season at higher elevations (Li and Yang, 2004). Long-term observations of high-elevation Central Alpine afforestations of *Pinus cembra* and *Larix decidua* also reported annual height growth rates commonly on the order of a few decimetres per year, although higher values may occur for *Larix decidua* under favorable conditions (Giunta et al., 2026). Therefore, over a 2–4 year temporal offset, expected height growth would generally be much smaller than the 5–10 m negative bias observed here for maximum canopy height. Moreover, because the Meta/WRI CHM mostly represents a later time window than the ALS reference, normal tree growth would be expected to increase Meta/WRI heights relative to ALS, not produce systematic underestimation. The robustness of ALS data under temporal offsets is further supported by previous work demonstrating that ALS-derived metrics can remain reliable for forest inventory and ecological applications even with lags exceeding a decade (McRoberts et al., 2018; Hill and Hinsley, 2015).

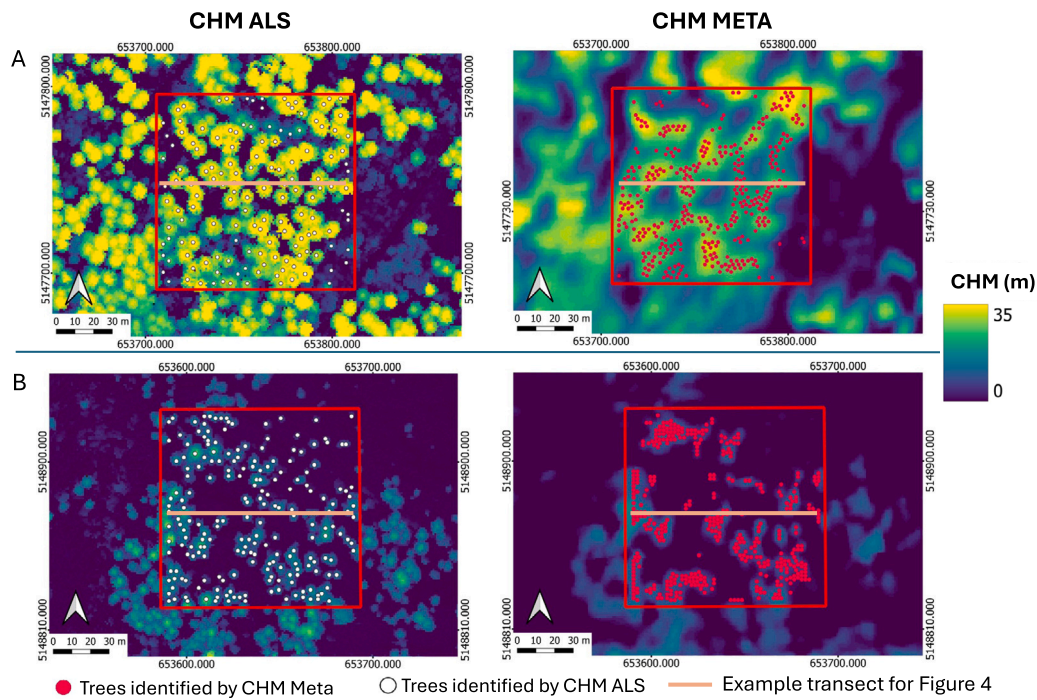


Fig. 6. Trees identified using the ALS CHM and Meta/WRI CHM in two random areas (Area A with large canopy cover and Area B with sparse canopy cover) in Rumo. The background shows both the CHMs of the same area (left the ALS CHM, right the Meta/WRI CHM). The locations and number of identified trees differed considerably between the ALS CHM and the Meta/WRI CHM. The orange line represents a transect used in Fig. 4 to display a side view in 2D, showcasing the ALS point cloud alongside the ALS CHM and the Meta/WRI CHM.

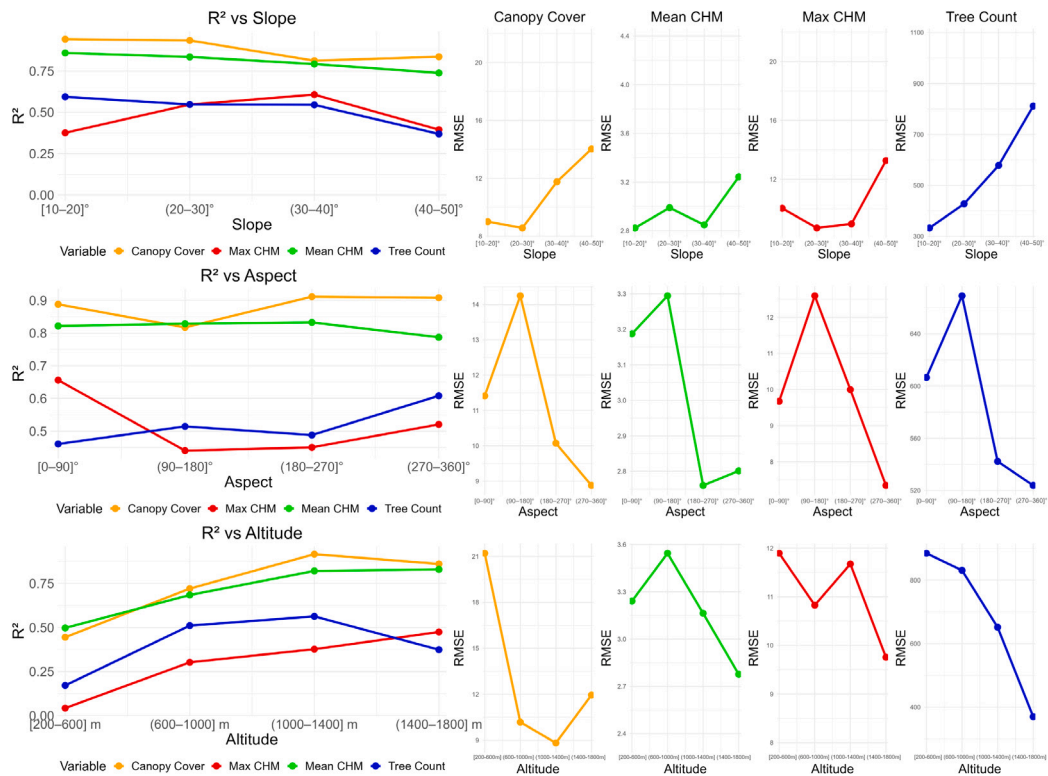


Fig. 7. Relationships between accuracy (R^2 and RMSE) of the evaluated metrics (canopy cover, mean CHM, maximum CHM, and tree count) and terrain characteristics (slope, aspect and altitude).

Taken together, these considerations indicate that temporal mismatch alone is unlikely to explain the magnitude and systematic direction of the observed height underestimation, which instead primarily reflects limitations inherent to the Meta/WRI CHM product.

Our results highlight a clear limitation of the Meta/WRI CHM for estimating tree count and positions (Fig. 6). The analysis of tree count relied on a tree detection algorithm applied to both the Meta/WRI and ALS-derived CHMs. Therefore, any discrepancies observed in tree number estimates primarily reflect limitations of the Meta/WRI CHM compared to the ALS CHM, rather than methodological constraints of the algorithm, which has demonstrated strong performance in mountainous forests (Zaforemska et al., 2019; Dalponte and Coomes, 2016). Although our analysis was limited to five sites within Alpine forests, which may restrict the generalizability of the results to other forest types or regions, the finding that the Meta/WRI CHM exhibits reduced sensitivity to variations in canopy height — affecting its ability to accurately represent individual trees — is consistent with previous studies across diverse forest types (Moudrý et al., 2024a; Chen et al., 2025; Dong et al., 2025). These discrepancies highlight the challenges of using global predicted CHMs, which combine space-borne lidar and optical imagery, for estimating fine-scale forest structure metrics, particularly in complex or dense canopies. While such approaches may provide reliable estimates of canopy cover, their value diminishes in dense forests where optical imagery can saturate, making it difficult to differentiate individual trees (Liu et al., 2024). Therefore, ALS-based canopy cover estimates remain essential for capturing three-dimensional structural information that predicted CHMs cannot yet reliably provide (Dong et al., 2025).

5. Conclusion

This study provides a comprehensive evaluation of the recently released 1-meter resolution Meta/WRI Global CHM, focusing on its accuracy and reliability for estimating canopy metrics within Alpine forest ecosystems. Our findings demonstrate that, within the evaluated Alpine forest sites of northern Italy, the Meta/WRI CHM provides reliable estimates of canopy cover (i.e., distinguishing forested and non-forested areas) and, to some extent, mean canopy height. However, under these mountainous conditions, it considerably underestimates maximum canopy height, which is a key metric for applications such as above-ground biomass estimation. Most importantly, tree count and crown size estimates exhibit substantial discrepancies: the Meta/WRI CHM considerably overestimates the number of trees and fails to accurately represent their positions and crown dimensions, making it unsuitable for such tasks. These limitations likely arise from a combination of factors, including optical signal saturation, shadowing in steep terrain and probably by limited representation of European mountain forests in the model training data. We emphasize that users should be aware of these limitations and that, for applications in Alpine forest environments similar to those evaluated here, the Meta/WRI CHM is best suited for stand- to landscape-scale assessments of canopy cover and mean canopy height, whereas airborne laser scanning data should be preferred where available for applications requiring accurate estimates of maximum canopy height or individual-tree attributes. While the Meta/WRI CHM offers substantial advantages in terms of spatial resolution, coverage, and accessibility, particularly in regions lacking ALS data, further refinement is needed to improve its accuracy in structurally complex mountainous forests. Since the completion of our analyses, an updated version of the global canopy height product, CHMv2, has become available (Brandt et al., 2026). Future work should assess whether this new version can reduce the limitations identified here, particularly the underestimation of maximum canopy height and the poor representation of fine-scale individual-tree structure, through validation against geographically diverse ALS reference datasets.

CRedit authorship contribution statement

Michele Torresani: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vítězslav Moudrý:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher R. Hakkenberg:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Vojtěch Barták:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Duccio Rocchini:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization. **Stefano Puliti:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Paweł Hawryło:** Writing – review & editing, Investigation, Conceptualization. **Krzysztof Stereńczak:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Alexander Cotrina-Sanchez:** Writing – review & editing, Visualization, Software, Investigation, Conceptualization. **Gabriele Giuseppe Antonio Satta:** Writing – review & editing, Investigation, Conceptualization. **Luca da Ros:** Writing – review & editing, Investigation, Conceptualization. **Patrick Kacic:** Writing – review & editing, Conceptualization. **Roberto Tognetti:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization.

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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.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.ecoinf.2026.103950>.

Data availability

All data used in this study are publicly available and can be accessed free of charge, with links to each data source provided within the manuscript. The scripts used for data processing are available here: <https://github.com/mictorresani/Evaluating-the-reliability-of-the-1-meter-resolution-Meta-estimated-Global-Canopy-Height-map>.

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