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ARTICLE
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Comparison of three global canopy height maps and their applicability to biodiversity modeling: Accuracy issues revealed

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Abstract

Global mapping of forest height is an extremely important task for estimating habitat quality and modeling biodiversity. Recently, three global canopy height maps have been released, the global forest canopy height map (GFCH), the high-resolution canopy height model of the Earth (HRCH), and the global map of tree canopy height (GMTCH). Here, we assessed their accuracy and usability for biodiversity modeling. We examined their accuracy by comparing them with the reference canopy height models derived from airborne laser scanning (ALS). Our results show considerable differences between the evaluated maps. The root mean square error ranged between 10 and 18 m for GFCH, 9–11 m for HRCH, and 10–17 m for GMTCH, respectively. GFCH and GMTCH consistently underestimated the height of all canopies regardless of their height, while HRCH tended to overestimate the height of low canopies and underestimate tall canopies. Biodiversity models using predicted global canopy height maps as input data are sufficient for estimating simple relationships between species occurrence and canopy height, but their use leads to a considerable decrease in the discrimination ability of the models and to mischaracterization of species niches where derived indices (e.g., canopy height heterogeneity) are concerned. We showed that canopy height heterogeneity is considerably underestimated in the evaluated global canopy height maps. We urge that for temperate areas rich in ALS data, activities should concentrate on harmonizing ALS canopy height maps rather than relying on modeled global products.

KEYWORDS
canopy height, canopy structure, GEDI, habitat, heterogeneity, LiDAR, niche, SDM

INTRODUCTION

Forest ecosystems cover more than 4.1 billion ha of the Earth's surface and provide a number of services, including the regulation of the global carbon cycle and acting as reservoirs of unique species and/or high biodiversity. It is well recognized that the vertical structure of the forest, including canopy height, is directly associated with aboveground biomass (Fischer et al., 2019), primary productivity (Dănescu et al., 2016), and animal (Davies & Asner, 2014) and plant diversity (Cazzolla Gatti et al., 2017). This, together with the high level of forest ecosystem threat induced by climate change and human activity, places the fine-grain global mapping of forest height among the highest-priority variables to be monitored from space (Bergen et al., 2009; Lefsky et al., 2005; Skidmore et al., 2021).

Until recently, we lacked comprehensive global data on the spatial patterns of canopy height. This changed with the rise of spaceborne laser altimetry: Light detection and ranging (LiDAR) missions. The Ice, Cloud, and land Elevation Satellite (ICESat) mission, operational between 2003 and 2009, collected over 250 million observations of forested areas globally (Schutz et al., 2005). In 2018, NASA launched two spaceborne LiDAR missions that have since continuously been providing data on the 3D structure of the Earth's surface. Namely, the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) and the Global Ecosystem Dynamics Investigation (GEDI), onboard the International Space Station, the latter being specifically designed for vegetation mapping (Dubayah et al., 2020; Magruder et al., 2021).

Spaceborne LiDAR sensors collect data along discrete transects. Hence, they only provide discrete samples of forest structure. Hancock et al. (2021) estimated that with the current in-orbit technology, 12 satellites would be required to produce a continuous map of canopy structure at a 30-m resolution every five years. Therefore, to produce continuous maps of global forest heights at fine resolution, the currently common approach is to train statistical or machine learning models that combine direct measurements (e.g., ICESat, GEDI, ICESat-2) with spatially continuous ancillary data (e.g., Sentinel-2, Landsat) enabling the estimation of the desired variable at locations not directly measured by GEDI or ICESat (Bergen et al., 2009; Lefsky, 2010). Simard et al. (2011) combined canopy heights collected by ICESat and multiple environmental variables (e.g., tree cover, climate, altitude) to derive a global map of canopy height at 1-km spatial resolution. That map was used, for example, to assess the association between canopy height and global water availability (Klein et al., 2015) and to test the hypothesis of a global relationship between plant species richness and canopy height (Cazzolla Gatti et al., 2017).

Biodiversity modeling is one of the important use cases for global canopy height maps as they can be used to describe habitat heterogeneity (Bergen et al., 2009; Davies & Asner, 2014; Fischer et al., 2024; LaRue et al., 2023; Simonson et al., 2014). Habitat heterogeneity has long been recognized as a key landscape characteristic determining biodiversity patterns. It is assumed that more complex environments may provide more potential niches and, thus, harbor higher species diversity (so-called habitat heterogeneity and fractal biodiversity hypotheses; Cazzolla Gatti, 2016; Tews et al., 2004). For example, taller canopies with high structural heterogeneity may harbor higher biodiversity by providing more, and more varied, resources. Indeed, canopy height has been shown to play an important role in determining the diversity and distribution of various taxa (Coddington et al., 2023; Cooper et al., 2020; Feng et al., 2020; Gallerani et al., 2023; Marselis et al., 2019, 2022; Seavy et al., 2009; Tew et al., 2022; Walter et al., 2021). The same effect was observed for horizontal heterogeneity in canopy height (Fricker et al., 2021; Torresani et al., 2020; Wolf et al., 2012). Therefore, besides the accuracy of canopy height estimates, it is also essential to know the sensitivity of global canopy height maps to canopy height changes and how well they represent canopy heterogeneity, such as edges (i.e., transitions between forest and nonforest).

According to Bergen et al. (2009), the requirements for canopy height accuracy for biodiversity and habitat science are ±2 m (but preferably ±1 m) and a resolution of 25–30 m considering the spatial scale of species' relationships with habitat characteristics (Moudrý, Keil, et al., 2023; Šímová et al., 2019). For example, Lang et al. (2023) and Potapov et al. (2021) created global canopy height maps at 30- and 10-m spatial resolutions, respectively. More recently, Meta and World Resources Institute developed a global canopy height map at a 1-m resolution (Tolan et al., 2024). Still, despite their unprecedented spatial resolutions, modeled global canopy height maps suffer from limited accuracy related to, for example, the quality of input data and the accuracy of modeling procedures. Such errors will propagate to any subsequent analyses using these data, therefore it is important to have a good understanding of the limitations of these data products (Atkins et al., 2023; Bolton et al., 2013; Magruder et al., 2016). In addition, the reliability of predicted global maps is increasingly questioned, particularly concerning often unreliably high accuracy estimates provided by the authors, for example, because of the use of inappropriate validation strategies or nonrepresentative reference data (Duncanson et al., 2019; Meyer & Pebesma, 2022).

Therefore, in this study, we (1) evaluate the accuracy of three modeled global canopy height maps using airborne laser scanning (ALS) data in Switzerland, New Zealand, and California; (2) assess the sensitivity of global canopy height maps to changes in canopy height (i.e., how well they represent canopy heterogeneity); (3) analyze the effects of environmental characteristics on the accuracy of canopy height estimates; and, finally, (4) assess the usability of the global canopy height maps for biodiversity modeling using a virtual species approach (see Figure 1 for the overall workflow of the study).

MATERIALS AND METHODS

Study areas

We selected three study areas in the temperate biome (Olson et al., 2001) in California (USA), Switzerland, and New Zealand (Figure 2) based on ALS data availability between 2019 and 2021 (Table 1). All three sites are ecologically significant regions, each with unique ecosystems and biodiversity. Moreover, they are also renowned for their natural beauty and scenic landscapes. On the one hand, they share similarities in terms of diverse and complex topography; on the other hand, however, these landscapes differ in several aspects of their characters. While Mount Richmond Forest includes hills and valleys, Entlebuch is a typical prealpine landscape with relatively gentle and undulating topography, and Trinity Alps represent a rugged mountain range with complex topography and high peaks. In terms of land cover, all these regions are forested and host a wide variety of ecosystems. Trinity Alps feature high-altitude landscapes with natural forests. This contrasts with the lower-lying terrain found in the Mount Richmond Forest, consisting of grasslands, native and plantation forests, and the cultural landscape of Entlebuch, which includes both cultivated lands, woodlands, and forests.

Trinity Alps Wilderness

The Trinity Alps Wilderness is the second largest wilderness area in California with over 200,000 ha of land. The Trinity Alps are a subrange of the Klamath Mountains and are characterized by rugged subalpine topography. The Trinity Alps region has the second-greatest number of conifer species of any place in the world. They form mixed conifer forests (*Pinus ponderosa*, *Pinus lambertiana*, *Pinus contorta*, *Abies concolor*, *Pseudotsuga menziesii*, *Calocedrus decurrens*), red fir forests (*Abies magnifica*, *Pinus jeffreyi*, *Pinus monticola*), or subalpine forests (*Pinus balfouriana*, *Pinus albicaulis*, *Tsuga mertensiana*) (Ferlatte, 1974).

Entlebuch Biosphere Reserve

The cultural landscape of Entlebuch was endorsed as a UNESCO Biosphere Reserve in 2001. The Reserve encompasses almost 40,000 ha of mostly prealpine and alpine mountain chains, forests, agriculturally utilized meadows, and small settlements in the center of Switzerland. At lower altitudes beech (*Fagus sylvatica*) is often naturally dominant, whereas in mountain forests the dominant species are spruce (*Picea abies*) and larch (*Larix decidua*).

Mount Richmond Forest

The study area comprises mainly the northern part of the Marlborough region (South Island of New Zealand),

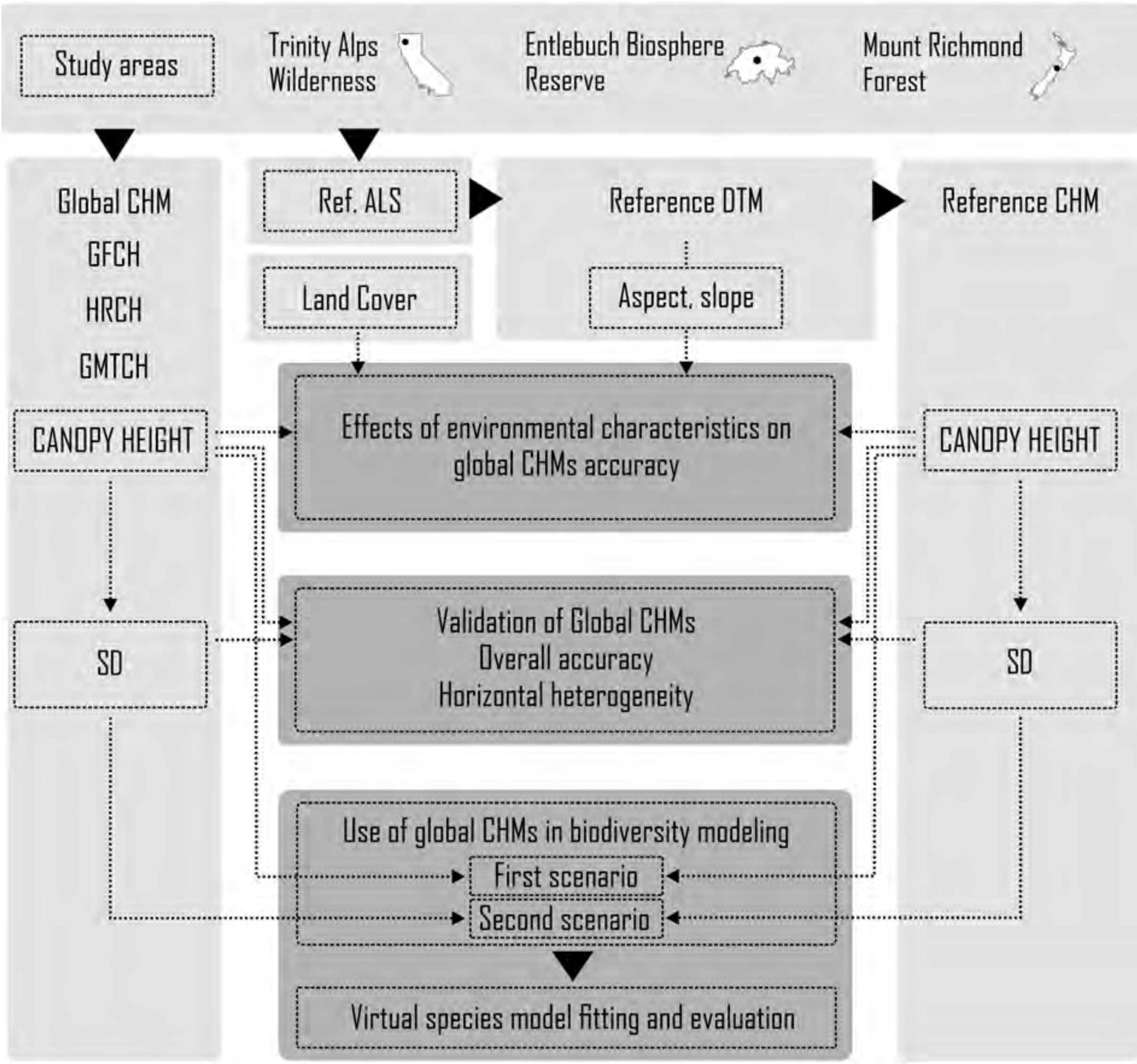

FIGURE 1 Workflow of the study. ALS, airborne laser scanning; CHM, canopy height model; DTM, digital terrain model; GFCH, global forest canopy height (Potapov et al., 2021); GMTCH, global map of tree canopy height (Tolan et al., 2024); HRCH, high-resolution canopy height model of the Earth (Lang et al., 2023).

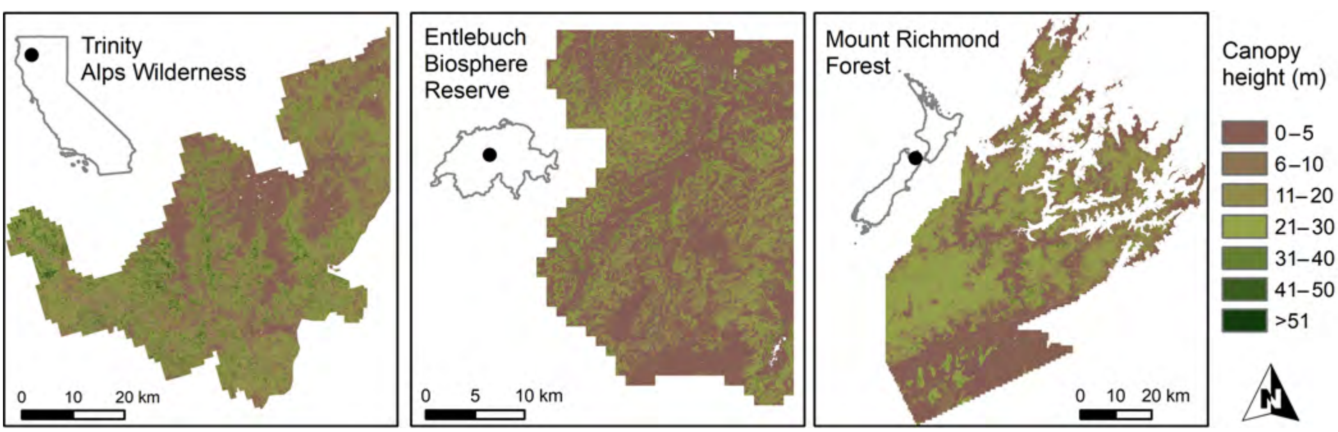

FIGURE 2 Location, and canopy height within the study areas.

TABLE 1 Study areas and light detection and ranging (LiDAR) data characteristics.

Study area	Area (km^2)	Altitude (m)	LiDAR acquisition (year)	Horizontal datum	Vertical datum	Density (points m^{-2})
Trinity Alps Wilderness	2588	600–2750	2019–2020	NAD 1983	NAVD 88	8
Entlebuch Biosphere Reserve	803	500–2350	2019	LV95	LN02	5
Mount Richmond Forest	6267	0–1760	2020–2021	NZGD 2000	NZVD2016	9

including the Mount Richmond Forest Park and the valley of the Wairau River (Figure 2). Mount Richmond Forest is a forest park established in 1977 in the South Island of New Zealand. The park covers an area of almost 166,000 ha. It is covered with relatively unmodified vegetation including native beech and plantation forests (*Nothofagus* spp.), dense native manuka (*Leptospermum scoparium*) and kanuka (*Leptospermum ericoides*) forests, and pastures. South of the Wairau River, grassland is the main vegetation cover.

Reference ALS data

The ALS data for the Trinity Alps Wilderness meet the requirements of the 3D Elevation Program (3DEP), which is managed by the U.S. Geological Survey and designed to collect high-quality LiDAR data for the conterminous United States. The minimum absolute vertical accuracies at the 95% confidence level for 3DEP are 20 and 30 cm in nonvegetated and vegetated terrain, respectively (Stoker & Miller, 2022). The ALS data for Entlebuch were collected as a part of an acquisition campaign to obtain Switzerland-wide LiDAR data. Their reported planimetric and altimetric accuracies are 20 and 10 cm (1 sigma), respectively (Federal Office of Topography in Switzerland). The ALS data for the Mount Richmond Forest were collected as a part of an acquisition campaign to obtain the New Zealand National Elevation Model. The minimum planimetric and altimetric accuracies for vegetated and nonvegetated areas are 50 and 10 cm, respectively (National Elevation Programme of New Zealand).

Data preprocessing

The classified ALS point clouds were processed in LAStools (version 220613; academic license). The data were divided into 2-km tiles. A buffer of 10 m was assigned to each tile to avoid edge effects when generating digital terrain models (DTM) and canopy height models (CHM). DTMs were generated at a 1-m resolution from points classified as ground using the blast2dem function of LAStools. Subsequently, DTMs were aggregated (using mean cell values) to the resolution of evaluated global canopy height maps (i.e., at 10 and 30 m). The point clouds were subsequently height-normalized using the lasheight function of LAStools, which calculates the height of each point above the terrain. CHM were generated at a 1-m resolution from the normalized point cloud using the lasgrid function of LAStools. To create the CHM, we used the highest returns in individual cells; each return was represented by a small circle (10 cm) to avoid creating pits in the CHMs (Khosravipour et al., 2014). Points classified as noise (class 7 and 18), buildings (class 6), water (class 9), or bridges (class 17) were not considered during CHM generation (LAS Specification, 2019). CHMs were subsequently aggregated (using maximum height values within the cell) to the resolution of evaluated global canopy height maps (i.e., at 10 and 30 m). In addition, cells with an estimated predictive uncertainty higher than 45 m (Lang et al., 2023) as well as cells with a canopy height above 60 m (Entlebuch, Mount Richmond Forest), and 70 m (Trinity Alps Wilderness) were removed, as these values are higher than maximum tree height in the respective study areas and were assumed to be outliers. Of approximately 70.5 million cells, only 421 were removed in this way.

Global canopy height maps

Global forest canopy height

Potapov et al. (2021) published a global forest canopy height (GFCH) map for the year 2019, with a spatial resolution of 30 m (https://glad.umd.edu/dataset/gedi/). They used Landsat and Shuttle Radar Topography Mission (SRTM) data and a regression tree algorithm to extrapolate GEDI Collection 1 canopy height measurements acquired between April and October 2019. They used the 95th percentile of energy return height relative to the ground (RH95) as the estimate of canopy top height. To ensure high data quality, they used only observations collected at night by GEDI's power beams

(Dubayah et al., 2020), with beam sensitivity ≥0.9 and with the agreement of the predicted ground elevations among the six algorithm setting groups within ≤2 m (see tab. 5 in Hofton et al., 2020). In addition, they excluded observations collected during the leaf-off season in temperate and boreal forests. This resulted in a sample size of 372 million GEDI footprints, 10% of which were used for validation. More recently, an updated version for the year 2020 using GEDI Collection 2 data with better geolocation accuracy has become available (https://glad.umd.edu/dataset/GLCLUC2020; Potapov et al., 2022). Here, however, we stick to using the 2019 version (see also Potapov et al., 2022 and Table 2 for a comparison of the two versions).

High-resolution canopy height model of the Earth

Lang et al. (2023) created a high-resolution canopy height model of the Earth (HRCH) for the year 2020 with a spatial resolution of 10 m (https://langnico.github.io/globalcanopyheight/). They used a deep convolutional neural network to integrate GEDI data acquired between April and August of both 2019 and 2020 with Sentinel-2 images of the lowest cloud coverage between May and September 2020. They defined the canopy top height as the relative height at which 98% of the energy was returned (RH98). They filtered out GEDI observations with clouds or snow-covered images. The sample size consisted of 600 million GEDI footprints, 20% of which were used for validation.

Global map of tree canopy height

Meta and World Resources Institute created a global map of tree canopy height (GMTCH). The map was generated in three steps: (1) the extraction of features from a self-supervised model trained on high resolution (~1 m) imagery from WorldView-2, WorldView-3, and Quickbird II satellites, covering the years 2009 through 2020 (80% of the imagery is from the 2018 to 2020 period). The imagery consisted of 18 million "cloud free" satellite images of red, green, and blue (RGB) bands, with approximately 0.5-m resolution, from across the globe; (2) supervised training of a dense prediction decoder using pairs of ALS CHM and RGB satellite images; and (3) postprocessing using a convolutional network trained on 13 million GEDI observations to correct a potential bias coming from a geographically limited source of supervision (Tolan et al., 2024). The dataset creates a global baseline of tree canopy height with a spatial resolution of approximately 1 m; however, for practical reasons, especially to improve visualizations (i.e., comparability with other models) and computational time, we have aggregated the GMTCH to the resolution of 10 m (using maximum values).

Validation of global canopy height maps

Overall accuracy

We examined the accuracy of HRCH (Lang et al., 2023), GFCH (Potapov et al., 2021), and GMTCH (Tolan et al., 2024) by comparing them with the reference ALS CHMs. The ALS CHMs are considerably more accurate compared to global canopy height maps and can thus be used as the reference dataset (true canopy height). As all global maps represent canopy top height, we used maximum canopy height at 10- and 30-m resolutions, respectively (i.e., we aggregated ALS CHMs using focal statistics type maximum). Subsequently, we calculated vertical differences between the modeled global canopy height maps and CHMs, using pairwise combinations on

TABLE 2 Accuracy measures of the high-resolution canopy height model of the Earth (HRCH), the global forest canopy height (GFCH) version for the years 2019 and 2020, and the global map of tree canopy height (GMTCH) for individual study areas based on comparison with airborne laser scanning-derived canopy height models.

	HRCH		GFCH 2019 (2020)		GMTCH	
Locality	**ME (m)**	**RMSE (m)**	**ME (m)**	**RMSE (m)**	**ME (m)**	**RMSE (m)**
Trinity Alps Wilderness	4.2	11.2	−14.3 (−14.1)	18.3 (18.0)	−12.6	16.7
Entlebuch Biosphere Reserve	5.9	10.5	−7.1 (−7.6)	11.8 (12.2)	−6.8	10.9
Mount Richmond Forest	4.8	8.8	−4.4 (−4.6)	9.7 (9.6)	−7.2	10.2
Reported by Potapov et al. (2021)			−3.8	9.1		
Reported by Lang et al. (2023)	−4.8 to 5.9	2.8–9.6	−7.9 to −1.0	5.2–12.0		
Reported by Tolan et al. (2024)					0.6	4.4

Abbreviations: ME, mean error; RMSE, root mean square error.

a cell-by-cell basis. We used the differences to calculate error metrics for each study area; namely, we calculated the mean error (ME) and root mean square error (RMSE), expressed as:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}\left(h_{\mathrm{GCHM}i} - h_{\mathrm{REF}i}\right)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_{\mathrm{GCHM}i} - h_{\mathrm{REF}i}\right)^2}$$

where $h_{\mathrm{GCHM}i}$ is the ith canopy height from the global canopy height map, $h_{\mathrm{REF}i}$ is the corresponding "true" canopy height from the reference ALS CHM, and n is the number of samples.

Horizontal heterogeneity

CHMs provide a representation of habitat heterogeneity. We used the SD of canopy height to estimate horizontal heterogeneity from the modeled global canopy height maps (HRCH, GFCH, GMTCH) and from ALS data. Selecting the appropriate resolution is an important aspect of evaluating the effects of fine-scale habitat heterogeneity on biodiversity. The resolution should be as close as possible to the ecological scale at which a focal species is expected to respond to habitat heterogeneity (see the review by Moudrý, Keil, et al., 2023). Prior studies evaluating the effects of fine-scale habitat heterogeneity on biodiversity, for example, in birds, have shown that resolutions ranging from hundreds of meters to a few kilometers are appropriate for modeling (Hunt et al., 2023; Moudrý et al., 2021; Roilo et al., 2023; Suárez-Castro et al., 2022). Besides, the resolution of all datasets is relatively fine (i.e., 1, 10 and 30 m, respectively), and it is, therefore, likely that studies adopting this data will aim for fine resolution. Therefore, we evaluated the accuracy of canopy height horizontal heterogeneity at a 300-m resolution rather than a coarser one.

Use of global CHMs in biodiversity modeling

Understanding the interactions between species and their environment is crucial for predicting species distribution patterns and habitat use, which in turn enhances biodiversity conservation and management. Species distribution models (SDMs) are extensively used to assess species-environment relationships and to predict species distributions across spatial and temporal scales. However, despite their widespread use, SDMs face significant challenges associated in particular with the quality of input data (Araújo et al., 2019; Fourcade et al., 2018; Gábor et al., 2024; Rocchini et al., 2011).

Simulation of virtual species

The virtual species approach is widely used to exemplify the effect of input data (in this case global canopy height datasets) error on SDMs (e.g., Meynard & Kaplan, 2013; Moudrý, 2015; Zurell et al., 2010). We used a simulated virtual species to ensure the complete knowledge of species distribution in order to enable a proper assessment of model performance without confounding effects of real data, such as positional uncertainty of occurrence data, species response grain, or shape of the response curve (e.g., Gábor et al., 2022, 2023; Zarzo-Arias et al., 2022). The simulated species' niche preference is an indirect way to illustrate the potential errors that could arise when predicting species' habitat preferences using global CHMs.

We first defined the response of virtual species to the canopy characteristics using the ALS CHM. As mentioned, canopy height and horizontal heterogeneity in canopy height are important determinants of the diversity and distribution of various taxa (e.g., Feng et al., 2020; Fricker et al., 2021). Therefore, we simulated two distinct relationships (response functions) between species occurrence and an environmental variable to generate environmental suitability. In the first scenario, we defined a virtual species with specific habitat requirements in terms of canopy height. The response to canopy height was defined as the logistic response function with the following parameters: alpha = −7, beta = 20. Alpha drives the slope of the curve, while beta controls its inflection point. Hence, this virtual species might represent a forest species (e.g., bird) preferring higher canopies. As mentioned in the Introduction, habitat heterogeneity is one of the most important factors affecting species distributions and diversity. Therefore, in the second scenario, we defined virtual species habitat requirements in terms of horizontal heterogeneity in canopy height using the SD of the canopy height. The response function was defined as Gaussian. The parameters of the response differed slightly for each study area according to canopy height heterogeneity in respective areas: Trinity Alps Wilderness (10 ± 2 m, mean ± SD), Mount Richmond Forest (7 ± 3 m), Entlebuch Reserve (7 ± 3 m). Hence, this virtual species represents a species preferring moderate canopy height heterogeneity.

We adopted a probabilistic approach (logistic function with alpha = −0.15 and beta = 0.65) to convert the environmental suitability raster into the probability of occurrence, which is subsequently used to randomly sample presences and absences. We simulated the sampling of equal numbers of presences and absences—namely, 800 samples for the first scenario and 400 for the second, respectively. We always used data of the same resolution to generate the virtual species and to fit the model. This approach assumes that each species interacts with the environment at a single scale (McGarigal et al., 2016; Moudrý, Keil, et al., 2023) defined by the resolution of CHMs used to generate the virtual species. All simulations were undertaken in R v.3.4.3, using the virtualspecies package (Leroy et al., 2016).

Virtual species model fitting and evaluation

It is customary to fit the Gaussian response with a polynomial model. We used generalized linear models (GLMs) with binomial error distribution and logit link function. For the first scenario, we included only linear terms. For the second scenario, both linear and quadratic terms of habitat heterogeneity were included because of the known Gaussian shape of the response functions. We modeled the species distribution using the canopy heights derived from ALS data (same as used for the virtual species generation) as well as using both modeled global canopy height maps.

To evaluate the models, we split the sampled presences–absences into test (50%) and training (50%) datasets. We ran the entire process from species generation to model evaluation 25 times. Each repetition provided a different presence–absence distribution (Leroy et al., 2016). We evaluated the model calibration by plotting the estimated environmental relationships. We assessed the model discrimination capacity by the area under the curve (AUC) of the receiver operating characteristic plot (Fielding & Bell, 1997).

RESULTS

Overall accuracy

The mean error of HRCH shows a positive vertical offset when compared to the maximum canopy height derived from ALS CHMs in all areas. On the other hand, the mean error of GFCH and GMTCH shows a negative vertical offset (Table 2). The RMSEs of all models are below 12 m except for GFCH and GMTCH in Trinity Alps Wilderness where the RMSE is greater than 16 m. Canopies taller than 40 m are considerably underestimated by all models, however, HRCH outperforms the GFCH and GMTCH in estimating their height. GFCH and GMTCH consistently underestimate the height of all canopies regardless of their height, while HRCH tends to overestimate the height of lower canopies and underestimate taller canopies (Table 3, Figure 3). The vegetation of low height (i.e., below 10 m) is considerably overestimated by HRCH, with GFCH and GMTCH providing better accuracy (Table 3, Figure 3). The BRT models of HRCH, GFCH, and GMTCH error explained between 58.2% and 73.1% of variability. All maps underestimated the horizontal heterogeneity of canopy height in all study areas (Figure 4). This coincides with an impaired ability to respond to changes in canopy height, as observed in the canopy height profiles, especially in the case of HRCH (Figure 5). Finally, the canopy height accounted for most of the variability in the global CHMs error, while the effects of slope and orientation were relatively weak (Appendix S1: Table S1). The accuracy of global canopy height maps deteriorated with the increasing slope and the relationship between the accuracy and terrain orientation seemed increasingly evident for greater slopes (Appendix S1: Figure S1).

Biodiversity modeling accuracy

Our results show a decrease in the discrimination ability of the models (i.e., AUC values) when the models are fitted using the global canopy height maps compared to the reference ALS data for both scenarios (Figure 6). For the first scenario (i.e., increasing probability of occurrence with increasing canopy height), the drop was relatively low, and the global models performed well in capturing these relationships. Notably, the HRCH map demonstrated good performance (Figure 6). However, for the second scenario (i.e., species preferring moderate canopy height heterogeneity), the drop in discrimination ability was high and the global models failed to estimate the true relationship (Figure 6). In this scenario, the shape of the estimated environmental relationship was slightly closer to the virtual reality for GMTCH than for HRCH and GFCH. However, none of the models correctly identified the virtual species optimum, which led to the misidentification of the species' optimal niche by several meters.

DISCUSSION

Global CHMs accuracy

Our results show similar RMSEs as independent validation of GFCH and HRCH provided by Lang et al. (2023)

TABLE 3 Accuracy measures of the high-resolution canopy height model of the Earth (HRCH), the global forest canopy height (GFCH), and the global map of tree canopy height (GMTCH) with respect to canopy height derived from airborne laser scanning reference data.

	HRCH		GFCH		GMTCH	
Canopy height (m)	**ME (m)**	**RMSE (m)**	**ME (m)**	**RMSE (m)**	**ME (m)**	**RMSE (m)**
Trinity Alps Wilderness						
0–5	12	15	2	6	−2	3
5–10	12	15	−1	6	−5	6
10–20	9	12	−6	9	−8	10
20–30	5	9	−10	13	−12	14
30–40	0	7	−15	17	−17	19
40–50	−5	8	−20	22	−24	25
>50	−13	15	−27	29	−33	35
Entlebuch Biosphere Reserve						
0–5	12	13	2	4	0	2
5–10	10	12	−4	7	−5	6
10–20	7	9	−7	11	−9	10
20–30	1	5	−11	14	−12	14
30–40	−5	7	−13	15	−17	18
40–50	−11	12	−18	19	−24	25
>50	−23	24	−31	32	−41	42
Mount Richmond Forest						
0–5	10	11	0	4	−1	3
5–10	11	11	0	8	−3	5
10–20	7	9	−2	9	−6	7
20–30	1	5	−5	9	−11	12
30–40	−6	8	−11	13	−18	18
40–50	−15	15	−20	21	−26	27
>50	−25	25	−31	32	−38	38

Abbreviations: ME, mean error; RMSE, root mean square error.

in Mount Richmond Forest (Table 2). The RMSEs in the Entlebuch Biosphere Reserve and in Trinity Alps Wilderness are slightly higher—below 12 m for both maps, with GFCH in Trinity Alps Wilderness being the only exception. In that area, the RMSE of GFCH is greater than 18 m, which is likely related to the presence of large areas with tall canopies (Figure 2). The ME values of HRCH and GFCH found by us are consistent with those reported by Lang et al. (2023) (Table 2). Our results also support the recommendation by Lang et al. (2023) to filter out inaccurate predictions using the estimated predictive uncertainty map. Indeed, the estimated predictive uncertainty correlates well with the absolute canopy height error of the HRCH map, at least as far as errors up to 12 m are concerned, and can be used as a reliable estimate for the canopy height error (Appendix S1: Figure S2).

Estimation of canopy height using satellite images is typically hampered by the underestimation of tall canopies, with the height estimates saturating at around 30 m (Healey et al., 2020; Potapov et al., 2021). Our results show that GMTCH and GFCH consistently underestimate the height of all canopies regardless of their height. This is consistent with independent validation of GFCH provided by Lang et al. (2023) who showed that the GFCH map tends to underestimate canopy height in areas where HRCH only slightly overestimates it (see extended data in tab. 1 in Lang et al., 2023). Indeed, HRCH outperforms the GMTCH and GFCH in estimating the height of tall canopies (taller than 30 m; Table 3), consistent with the results of Lang et al. (2023) who highlighted that their approach reduces the saturation effect. However, Lang et al. (2023) reported that the

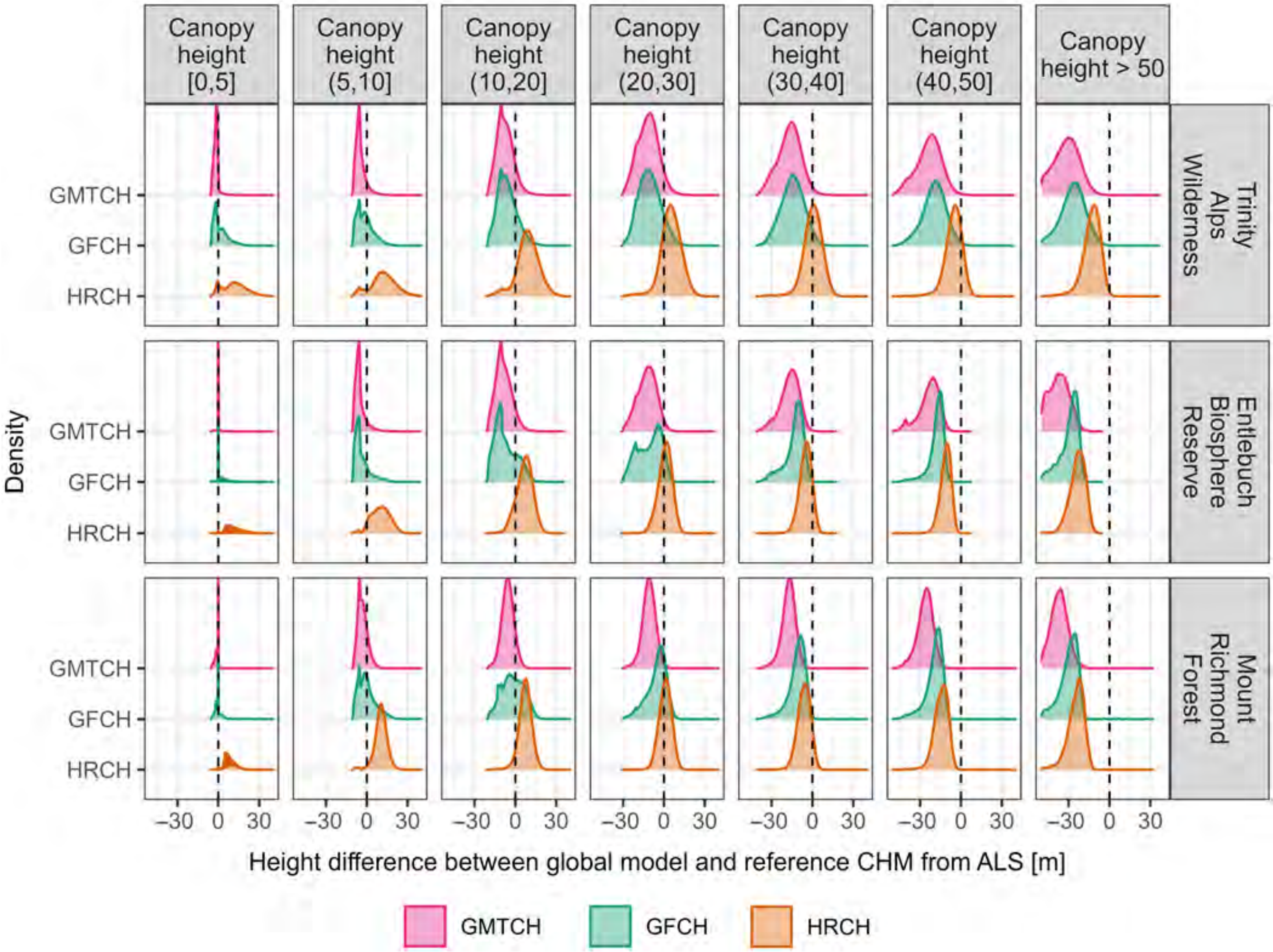

FIGURE 3 Density plots illustrate the distribution of canopy height differences between global maps and airborne laser scanning (ALS)-derived data, categorized by canopy height. GFCH, global forest canopy height (Potapov et al., 2021); GMTCH, global map of tree canopy height (Tolan et al., 2024); HRCH, high-resolution canopy height model of the Earth (Lang et al., 2023).

"price they paid" for improving the performance of tall canopies was a slight overestimation of low canopy heights. According to our results, however, this "price" is quite high, as the overestimation of low canopies in temperate biome can reach considerably high values (Table 3, Figure 3). HRCH overestimated the height of low canopies (up to 10-m high) on average by 10 m (Table 3). This is well illustrated in the canopy height profiles (Figure 5). For example, the mosaic of pastures and forests in the Entlebuch study area (Switzerland) appears as a continuous forest in the HRCH map (i.e., the transition between forest and nonforest remains unclear), while the GMTCH and GFCH maps correctly show zero canopy height in grasslands (Figure 5). The sensitivity of the GMTCH map to canopy height changes (i.e., transitions between forest and grasslands) is considerably improved compared to the HRCH and GFCH maps due to its finer resolution (Figure 5). In this context, Schwartz et al. (2023) reported that the resolution of HRCH appears to be coarser than 10 m. This could also be partly related to the fact that the effective spatial resolution of HRCH is coarser than the nominal 10-m ground sampling distance (Lang et al., 2023). This is a consequence of the GEDI footprint (~25-m diameter) and its misalignments caused by geolocation error (Roy et al., 2021). Surprisingly, according to Lang et al. (2023), this should not severely limit the usefulness of the map. However, in our opinion, overestimating data quality increases the risk of incorrect implications derived from its use, which can in effect lead to incorrect management decisions. For this reason, we believe that it should be the producer's responsibility not to overvalue their data product.

Biodiversity modeling

Our results clearly show that the use of global tree canopy height maps for biodiversity modeling allows the

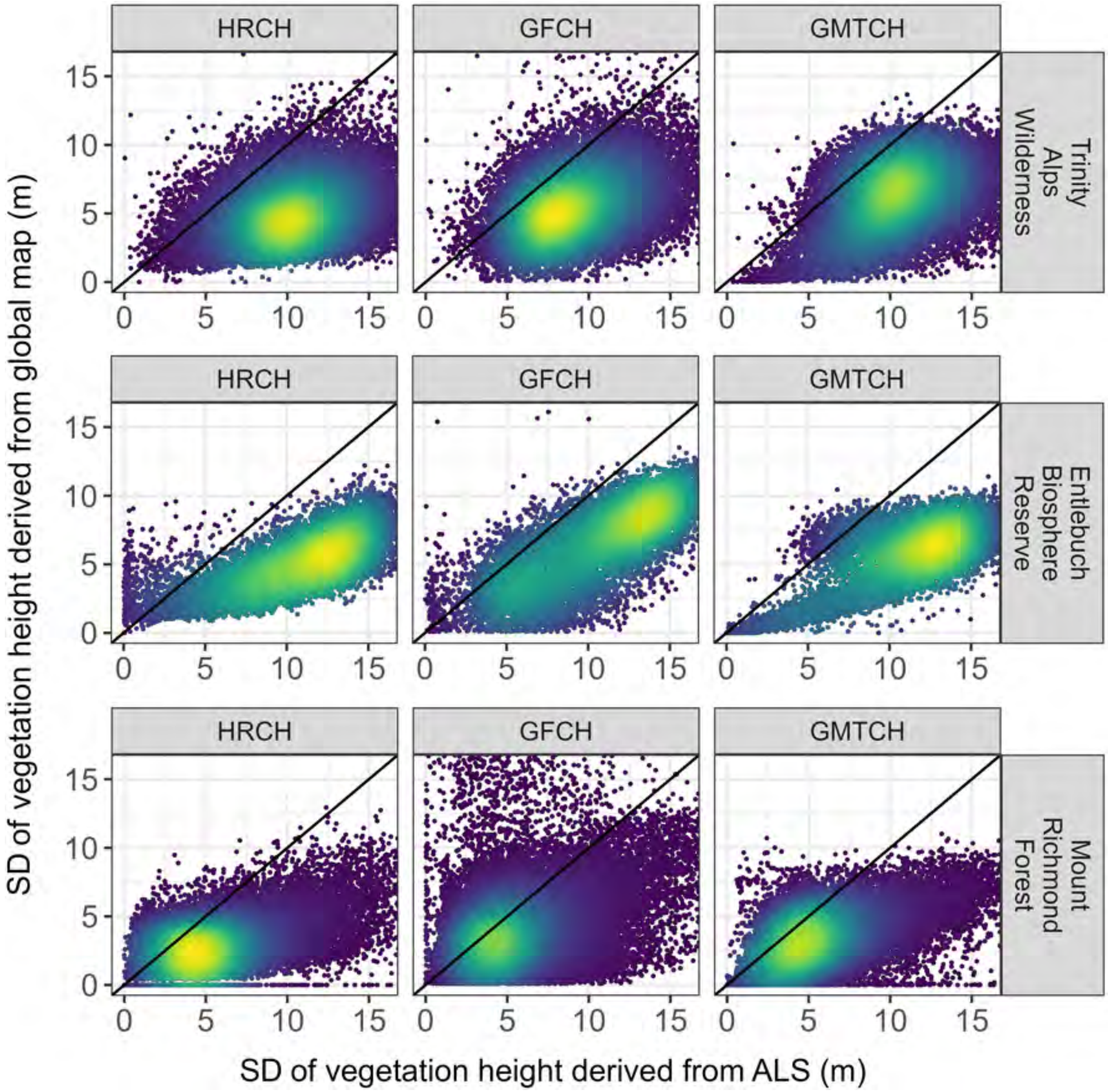

FIGURE 4 SD of canopy height derived from global canopy height models versus airborne laser scanning (ALS)-derived SD of canopy height. The solid line indicates $y = x$. Note that all maps considerably underestimate the horizontal heterogeneity of canopy height in all study areas. GFCH, global forest canopy height (Potapov et al., 2021); GMTCH, global map of tree canopy height (Tolan et al., 2024); HRCH, high-resolution canopy height model of the Earth (Lang et al., 2023).

estimation of simple relationships between species occurrence and canopy height (Figure 6). However, when derived indices such as canopy height heterogeneity are used, it leads to a considerable decrease in the discriminatory ability of the models and mischaracterization of species niches (but see Torresani et al., 2023 who showed the opposite). When using global canopy height maps, it is extremely important to take the accuracy of the maps and particularly of the derived indices (e.g., habitat heterogeneity and complexity) into consideration before including them in the modeling process.

In this study, we used a simplistic example that utilized a single predictor at a resolution corresponding to the known response grain of a virtual species, which was perfectly sampled without any deficiencies in occurrence data. This is, however, a very unlikely (if not impossible) combination. For example, multiple resolutions are typically tested when developing SDMs and this can considerably affect the propagation of errors from global CHMs (Gábor et al., 2022; McGarigal et al., 2016; Moudrý et al., 2018). Furthermore, deficiencies in species occurrence data, including positional accuracy (Gábor et al., 2023) and sampling bias (Rocchini et al., 2023), must also be taken into account. Failure to account for errors and their interaction can lead to misinterpretation of species–environment relationships and misidentification of areas important for species conservation. Nevertheless, the interaction of errors in species

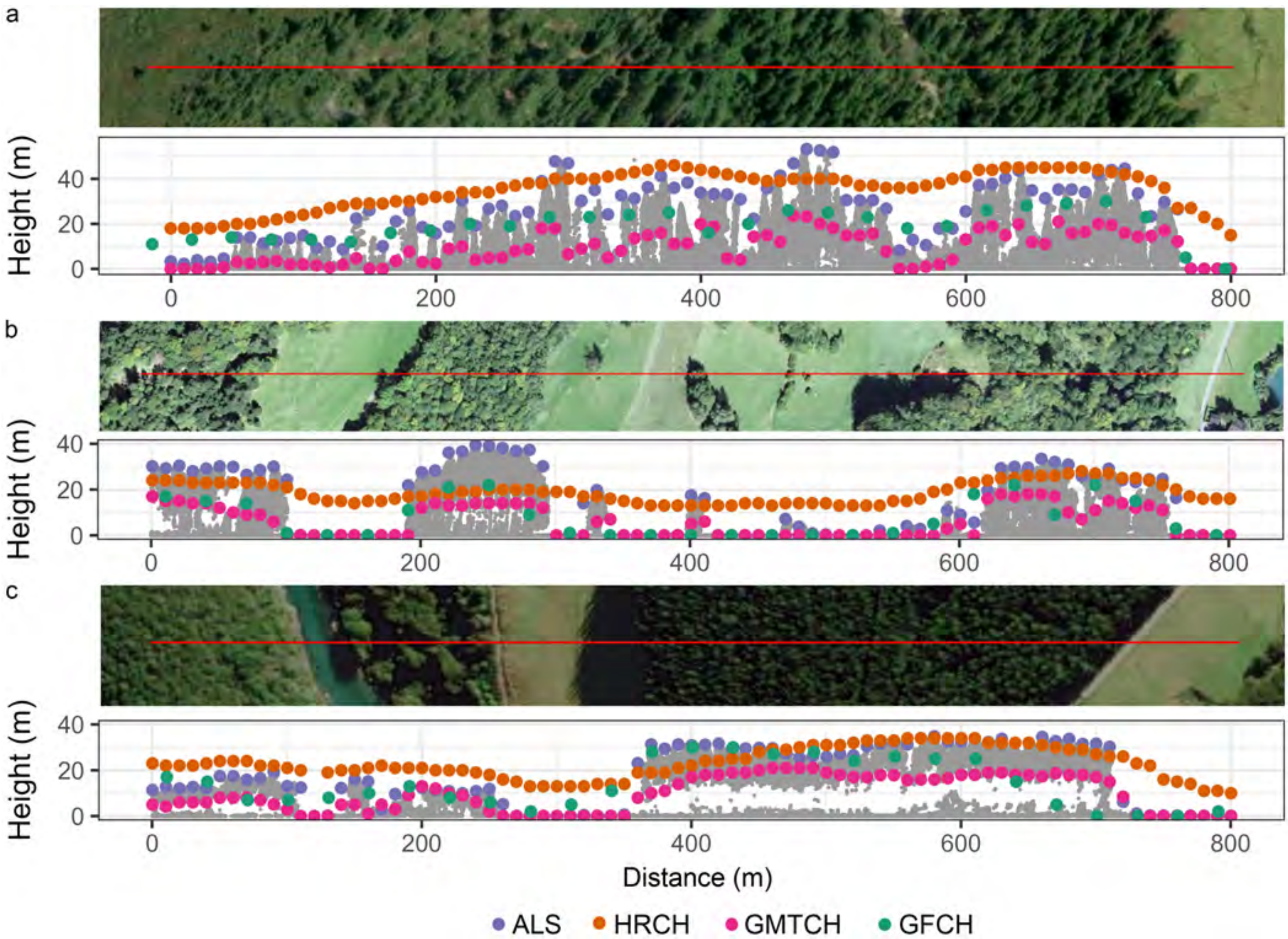

FIGURE 5 Representative canopy height profiles: (a) Trinity Alp Wilderness; (b) Entlebuch Biosphere Reserve; (c) Mount Richmond Forest (bottom). The profiles are 10-m wide. Note the impaired ability (particularly for HRCH map) to respond to changes in the canopy height (i.e., the transition between forest and nonforest remains unclear). For example, the mosaic of pastures and forests in the Entlebuch study area (bottom) looks like a forest with height ranging between 15 and 25 m in the HRCH map. In contrast, the GMTCH map performs relatively well in distinguishing between forest and nonforest areas. This is due to the considerably better resolution of the input data used to generate this map. However, the biggest underestimation of vegetation height was observed for the GMTCH. The data and code used to plot the canopy height profiles are available from Zenodo (see *Data availability statement*). ALS, airborne laser scanning; GFCH, global forest canopy height (Potapov et al., 2021); GMTCH, global map of tree canopy height (Tolan et al., 2024); HRCH, high-resolution canopy height model of the Earth (Lang et al., 2023).

occurrences and environmental predictors remains understudied (but see Standfuß et al., 2024).

Given the poor performance of global CHMs, we attempted to replace global CHMs with Normalized Difference Vegetation Index (NDVI) in the models to evaluate whether their use would be justified at all (see Appendix S1 for details on the methods). The NDVI is generally positively correlated with canopy structure, including its height (Gamon et al., 1995; Pascual et al., 2010). However, models using NDVI performed worse than those using global CHMs in both scenarios. In the first scenario, AUC values were 0.74, 0.67, and 0.74 for Trinity Alps Wilderness, Entlebuch Biosphere Reserve, and Mount Richmond Forest, respectively. This is considerably worse than the performance of global CHMs (Figure 6). In the second scenario, AUC values were below 0.60 in all study areas, which is again worse than the performance of the best global CHM. This suggests that the CHMs could have merit compared to indices derived more directly from the spectral data. However, further analyses involving "real" species and a combination of multiple variables (not just one, as in our simplifying case) are needed to validate this.

We showed that vertical bias in global CHMs can prevent researchers from getting the appropriate niche estimate. Local high-accuracy CHMs, such as those derived from ALS data, which are increasingly available through governmental agencies in Europe as well as in other parts

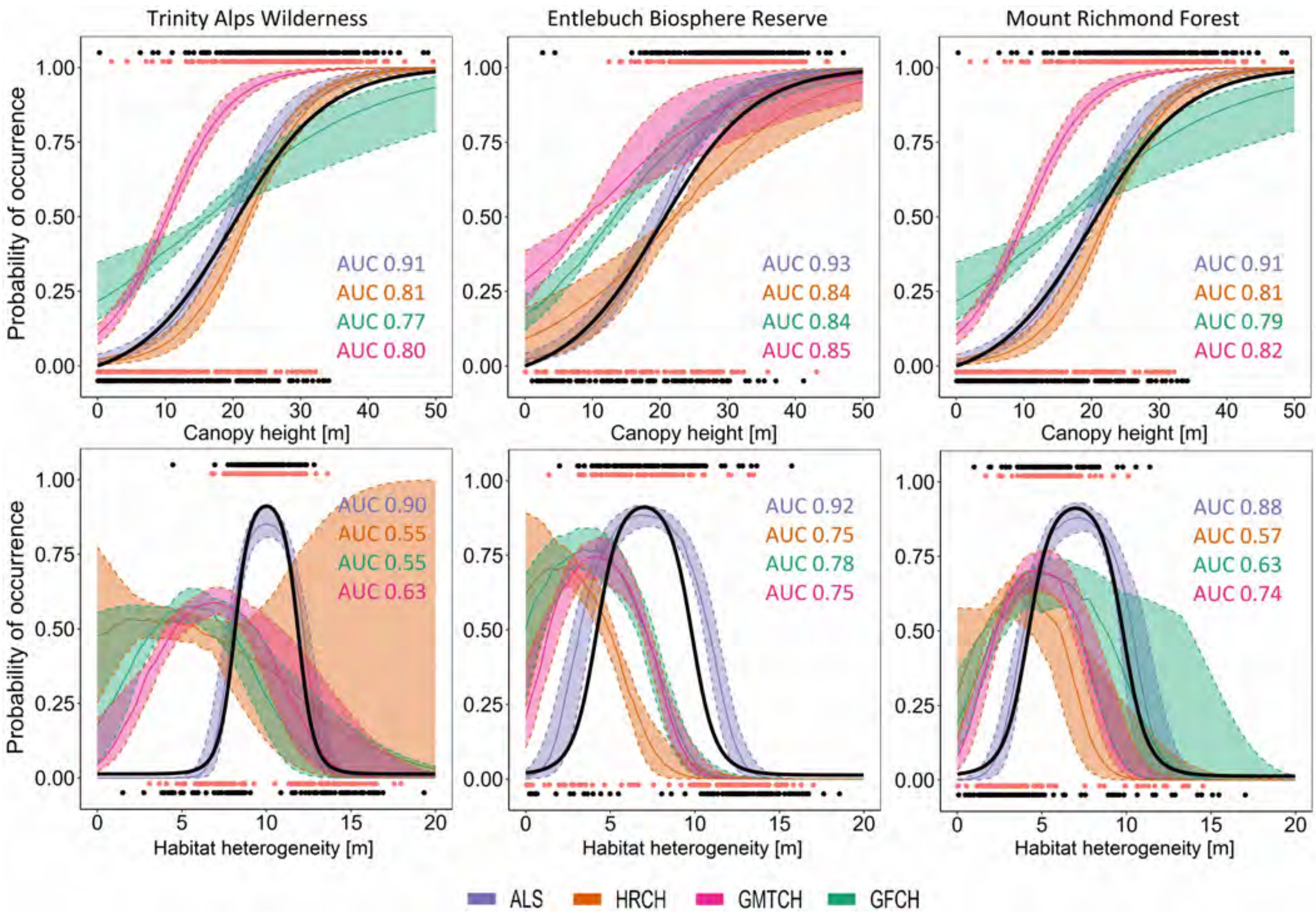

FIGURE 6 Modeled probability of species occurrence with respect to canopy height and habitat heterogeneity estimated with GLMs using ALS CHM, GFCH, GMTCH, and HRCH maps. The shaded areas represent the regions delimited by the 5th–95th percentiles of the estimated probability of occurrence obtained from 25 simulations. Black lines show the "true" relationships. Points represent presences and absences used for model training (black) and testing (red). The area under the curve (AUC) of the receiver operating characteristic plot characterizes the discrimination ability of the models. ALS, airborne laser scanning; GFCH, global forest canopy height (Potapov et al., 2021); GMTCH, global map of tree canopy height (Tolan et al., 2024); HRCH, high-resolution canopy height model of the Earth (Lang et al., 2023).

of the World, should thus be favored (e.g., Assmann et al., 2022; Kissling et al., 2023; Melin et al., 2017; Moudrý, Cord, et al., 2023; Stoker & Miller, 2022).

Way forward

Estimating forest characteristics, such as canopy height, using optical images is a challenging task because optical remote sensing is not designed to capture the vertical structure of vegetation and the physical associations between spectral signatures and vertical forest structure are still poorly understood (Goetz & Dubayah, 2011; Lang et al., 2023; Rodríguez-Veiga et al., 2017). Models could be improved by using large training datasets (Schwartz et al., 2022) and including additional suitable predictors that are known to affect canopy height, such as climatic and topographic variables (Klein et al., 2015; Simard et al., 2011; Tao et al., 2016; Wang et al., 2019). In addition, it might be valuable to train models with respect to land cover (Healey et al., 2020). For example, Lefsky (2010) developed models independently for broadleaf and needleleaf forests, and Simard et al. (2011) considered 12 land cover classes. Furthermore, it might be valuable to train models at a local scale. For example, Kacic et al. (2023) and Schwartz et al. (2023) developed CHMs using GEDI and Sentinel data for Germany and France, respectively. Schwartz et al. (2023) showed that their model considerably outperforms both HRCH and GFCH. This might be thanks to the improved ability of their approach to filter out unsuitable GEDI footprints. Furthermore, the models can be improved by removing

GEDI footprints on steep terrain (Bolton et al., 2013; Simard et al., 2011), which was not considered in either HRCH or GFCH. The terrain slope is an important factor known to cause bias in canopy height estimates from spaceborne LiDAR (Liu et al., 2021; Moudrý et al., 2022; Quirós et al., 2021). It is particularly problematic for full waveform large footprint LiDAR such as the Geoscience Laser Altimeter System (GLAS) onboard the ICESat satellite (e.g., Simard et al., 2011). The GEDI footprint size is considerably smaller, which reduces the effect of slope on canopy height estimates (Dubayah et al., 2020). However, our results still show an effect of slope and aspect on the accuracy of all maps (Appendix S1: Figure S1). If not accommodated for, such errors can propagate through the modeling and negatively affect canopy height predictions.

CONCLUSION

In this study, we investigated the agreement between three global canopy height maps and canopy height estimates derived from airborne LiDAR in temperate biomes. Our results show that there are large errors in the evaluated global maps. Tall canopies are underestimated by all models, however HRCH map (Lang et al., 2023) outperforms the GFCH (Potapov et al., 2021) and GMTCH (Tolan et al., 2024) maps in estimating their height. On the other hand, HRCH map appeared to be less sensitive to spatial heterogeneity in canopy height, resulting in more uniform canopy height predictions, than the GFCH and GMTCH maps which provided a better estimate of horizontal heterogeneity in canopy height.

Existing errors propagate through to subsequent analyses, which is particularly important for applications in biodiversity modeling as habitat heterogeneity is a key characteristic determining biodiversity patterns. Our virtual species experiments showed that biodiversity models using modeled global canopy height maps perform well for simple relationships, but lead to the mischaracterization of species niches when using derived indices (e.g., SD of canopy height). The modeled global canopy height maps are readily available in raster format, increasing the risk that users would prefer global products to the tedious processing of more accurate ALS data. It is, therefore, particularly important that users are aware of the errors and their impact on biodiversity modeling so they can make informed decisions. We suggest that for temperate areas rich in ALS data (e.g., Europe, the United States) activities should concentrate on harmonizing ALS canopy height maps rather than relying on modeled global products.

AUTHOR CONTRIBUTIONS

Vítězslav Moudrý conceived the ideas and analyzed the data. Vítězslav Moudrý and Lukáš Gábor performed the virtual species experiment. Vítězslav Moudrý led the writing with assistance from all authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The evaluated global canopy height maps, that is, the global forest canopy height (Potapov et al., 2021), the high-resolution canopy height model of the Earth (Lang et al., 2023), and the global map of tree canopy height (Tolan et al., 2024) are provided under Creative Commons Attribution 4.0 International License. The code used to generate virtual species and canopy height profiles (Gabor, 2022) is available from Zenodo: https://doi.org/10.5281/zenodo.7332716. The canopy height maps derived from airborne laser scanning (Moudrý & Gábor, 2023) are available from Zenodo: https://doi.org/10.5281/zenodo.7697253. The original airborne laser scanning point clouds used for the validation are sourced from the LINZ Data Service and OpenTopography (LINZ, 2023); Federal Office of Topography swisstopo (FOTS, 2023); and U.S. Geological Survey (USGS, 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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