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Assessing canopy height measurements from ICESat-2 and GEDI orbiting LiDAR across six different biomes with G-LiHT LiDAR

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Abstract

The height of woody plants is a defining characteristic of forest and shrubland ecosystems because height responds to climate, soil and disturbance history. Orbiting LiDAR instruments, Ice, Cloud and land Elevation Satellite-2 (ICESat-2) and Global Ecosystem Dynamics Investigation LiDAR (GEDI), can provide near-global datasets of plant height at plot-level resolution. We evaluate canopy height measurements from ICESat-2 and GEDI with high resolution airborne LiDAR in six study sites in different biomes from dryland shrub to tall forests, with mean canopy height across sites of 0.5–40 m. ICESat-2 and GEDI provide reliable estimates for the relative height with RMSE and mean absolute error (MAE) of 7.49 and 4.64 m (all measurements ICESat-2) and 6.52 and 4.08 m (all measurements GEDI) for 98th percentile relative heights. Both datasets slightly overestimate the height of short shrubs (1–2 m at 5 m reference height), underestimate that of tall trees (by 6–7 m at 40 m reference height) and are highly biased (>3 m) for reference height <5 m, perhaps because of the difficulty of distinguishing canopy from ground signals. Both ICESat-2 and GEDI height estimates were only weakly sensitive to canopy cover and terrain slope ($R^2 < 0.06$) and had lower error for night compared to day samples (ICESat-2 RMSE night: 5.57 m, day: 6.82 m; GEDI RMSE night: 5.94 m, day: 7.03 m). For GEDI, the day versus night differences varied with differences in mean sample heights for the day and night samples and had little effect on bias. Accuracy of ICESat-2 and GEDI canopy heights varies among biomes, and the highest MAE was observed in the tallest, densest forest (GEDI: 7.85 m; ICESat-2: 7.84 m (night) and 12.83 m (day)). Improvements in canopy height estimation would come from better discrimination of canopy photons from background noise for ICESat-2 and improvements in the algorithm for decomposing ground and canopy returns for GEDI. Both would benefit from methods to distinguish outlier samples.

1. Introduction

Plant height is a crucial component of plant ecological strategies (Westoby *et al* 2002, Díaz *et al* 2016), impacting light interception, competitive interactions, carbon storage, and water balance (Palmer 1989, Ryan and Yoder 1997, Savage *et al* 2017). Plant height is also an important part of a coordinated suite of life-history traits including survival and turnover rates, longevity, and seed mass, which determine how species live,

grow, and reproduce (Moles and Leishman 2008, Moles *et al* 2009). Spatially explicit and accurate tree height measurements are central to characterizing the spatial patterns of species- and ecosystem-level traits, including wood volume and biomass (Chave *et al* 2005), structural diversity (Staudhammer and LeMay 2001), net primary productivity (Ryan *et al* 1997, Pregitzer and Euskirchen 2004, Keeling and Phillips 2007, Yang *et al* 2011b), environmental stress (Marks *et al* 2016), and biodiversity (Bae *et al* 2019).

Accurate estimation of plant height across terrestrial ecosystems, often acquired through expensive and difficult data gathering practices, provides key parameters and constraints for dynamic vegetation and global carbon models (Purves and Pacala 2008, Le Toan *et al* 2011, Harper *et al* 2018). Until recently, information on canopy height depended largely on field measurements (Larjavaara and Muller-Landau 2013), which lack the spatial coverage required for regional and global modeling. Field-based height measurements can also produce erratic and biased estimates (Wildi 2017).

The advances in Light Detection and Ranging (LiDAR) technology enable us to tackle the challenges in canopy height estimation (Holmgren *et al* 2003, Stovall *et al* 2019). LiDAR instruments measure the travel time and range of laser pulses between the sensor and ground objects, thus providing potential to derive the elevation of the ground surface and vegetation canopies above the ground (Dubayah and Drake 2000). Airborne and terrestrial LiDAR are transforming the way we measure canopy structure at local scales via numerous studies and data collection practices across terrestrial ecosystems (Bradbury *et al* 2005, Wulder *et al* 2008, Yu *et al* 2018, 2020). However, both airborne and terrestrial LiDAR are restricted to relatively local scale sampling due to cost and time constraints. A new generation of spaceborne LiDAR instruments were recently developed for ecosystem assessments, management and carbon monitoring at large scale. NASA's Ice Cloud and land Elevation Satellite-2 (ICESat-2, launched in September 2018) and the Global Ecosystem Dynamics Investigation (GEDI, launched in December 2018) now provide canopy height estimation at near-global scale with unprecedented spatial resolution and structural information (Neuenschwander and Magruder 2016, Popescu *et al* 2018, Dubayah *et al* 2020a).

By providing near-global canopy height products, ICESat-2 and GEDI hold the potential to improve global ecological structure measurements (Potapov *et al* 2021) and enhance the ability to model ecosystem services. The two missions use different technologies each with strengths and weaknesses for height retrieval, and have differing sensitivities to topography, phenology, and canopy configurations (Neuenschwander and Magruder 2016, Duncanson *et al* 2020, Dubayah *et al* 2020a, Lang *et al* 2021).

A study of canopy height estimation in boreal forest in southern Finland showed that ICESat-2's strong beams acquired at night during summer had lower error, particularly in landscapes with relatively high canopy cover (>40%, Neuenschwander *et al* 2020). Using simulated ICESat-2 data, Duncanson *et al* (2020) suggested that ICESat-2 could be used to estimate biomass for short and open canopies. A study of 40 National Ecological Observation Network (NEON) sites found reduced accuracy for ICESat-2 for canopy height for slopes over 30° and taller canopies, and for day and weak beams compared to night measurements with the strong beam (Liu *et al* 2021). ICESat-2 tended to underestimate the canopy height of taller forests and overestimate the canopy height of dwarf shrublands (Liu *et al* 2021). A study of 12 sites in the USA (3 conifer forests, 3 deciduous forests, 2 Mediterranean forests, 2 tropical or sub-tropical grasslands, 1 desert, and 1 temperate grassland) showed that ICESat-2 canopy height measurements are better for conifer and broadleaf forests than in sparse grassland and savanna canopies (Malambo and Popescu 2021).

Studies that compared GEDI canopy height metrics to metrics derived from airborne LiDAR have been summarized by Wang *et al* (2022), showing the GEDI L1 data had root mean square errors (RMSE) for canopy heights that varied from 2.02 to 8.80 m depending on the study and relative height assessed (RH > 75 for all). For GEDI L2 data, RMSE for maximum canopy height (RH100) was 2.62 m across 33 National Ecological Observation Network (NEON) sites representing many forested ecosystems, as well as several grassland, shrub and agricultural sites (Wang *et al* 2022); for forested sites in Wang *et al* (2022), %RMSE was <25%. Several studies found that GEDI canopy height was sensitive to beam type (full power or coverage), day or night acquisition, canopy cover, slope, canopy height (Adam *et al* 2020, Liu *et al* 2021, Quiros *et al* 2021, Fayad *et al* 2021a, 2021b, Kutchartt *et al* 2022, Wang *et al* 2022), landscape heterogeneity and geolocation uncertainty (Roy *et al* 2021) and sensitivity selection for GEDI beams (Liu *et al* 2021).

This study aims to quantify and compare the errors and biases of canopy height estimation by ICESat-2 and GEDI over six distinct biomes. We examine how canopy height estimation for these two sensors compares with data from airborne LiDAR at relative heights at 50, 95, 98 and 100 percentile and how these comparisons are influenced by terrain slope, canopy cover, tree height, and data acquisition characteristics (beam type and time of day (day or night) for both ICESat-2 and GEDI and algorithm selection for decomposing the returned waveform for GEDI). We provide recommendations for use of and improvements to ICESat-2 and GEDI canopy height products.

2. Data and study sites

2.1. ICESat-2 and GEDI canopy height products

ICESat-2, launched in September 2018, utilizes 532 nm laser altimetry (Advanced Topographic Laser Altimeter System, ATLAS), to send laser pulses and record travel time of individual photons returned to ATLAS (Neuenschwander and Pitts 2019). Received photons are geolocated and their elevation estimated based on their round-trip travel time. The expected geolocation accuracy threshold of ICESat-2 is 6.5 m, and post-launch alignment calibration has largely improved the geolocation requirement to <5 m (Neuenschwander and Magruder 2019), with error assessments of 2.5 m for beam 6 and 4.4 m for beam 2 (Luthcke *et al* 2021). The ATLAS pulse repetition frequency provides measurements at 0.7 m intervals along-track with a swath width of 13 m. Each transmitted laser is split into three pairs of strong and weak beams, which generates six tracks, allowing a larger ground sampling. Returned photons are classified as ground, canopy, top of canopy or noise, based on local photon density and elevation distribution. In the two-dimensional space of elevation and along-track distance, signal photons reflected from ground and canopy are expected to be more clustered (thus at a higher density) than background noise photons. Ground and above-ground vegetation can then be further separated by analyzing the density and distribution of photons in local along-track segments (Neuenschwander *et al* 2020).

Canopy height of classified canopy photons is estimated as their vertical distance to the interpolated ground surface (using the ground photons). The along-track Land and Vegetation Height product (ATL08) comprises basic statistics of vegetation height and relative height metrics within 100 m along-track segments (Neuenschwander and Pitts 2019). Relative height metrics are the k th percentile of canopy height within each segment. To validate canopy height estimation, we selected four vegetation height metrics from the latest ATL08 products (Release 5), including relative height (k) at the 50th (RH50), 95th (RH95), 98th (RH98), and 100th (RH100) percentiles. Since background photon (noise) rates in sunlit conditions can be elevated, we compared night and day ICESat-2 acquisitions separately and compared estimates from the strong and weak beams (Liu *et al* 2021). ICESat-2 data from late 2018–mid 2020 were used for analysis.

The GEDI instrument was deployed on the International Space Station in December 2018 and moved to storage in March 2023 for a potential mission resumption in late 2024. GEDI uses a full-waveform LiDAR instrument, with three lasers emitting at 1064 nm wavelength (Dubayah *et al* 2020a). One of the three full power lasers is split into two coverage beams, resulting in four beams, with ground footprints of 25 m diameter. By rapidly shifting the outgoing beams by 1.5 m rad, these four beams produce eight tracks (four power and four coverage) spaced 600 m across-track at 60 m intervals along-track. The geolocation error of GEDI footprints was improved for the Release 2 with mean horizontal geolocation error of 10.2 m (Dubayah *et al* 2020b), and GEDI covers areas between 51.6° N to 51.6° S. Returned energy within each footprint is digitized to a maximum of 1246 bins, with a vertical temporal resolution of 1 ns (equal to ~ 15 cm vertical height resolution). The elevation and intensity of returned energy from each footprint create a waveform reflecting the 3D structure of that footprint. Waveforms are then processed to identify the ground, and canopy structure metrics such as canopy cover, relative height, and plant area profile, retrieved from the distribution profile of the returned energy above the estimated ground surface (Hofton *et al* 2019). Footprint-level relative height metrics are computed as the vegetation height of k th percentile of waveform energy relative to the identified ground. Four relative height metrics were used, RH50, RH95, RH98, and RH100, from level 2A footprint-level product (version 2), using quality criteria suggested by GEDI Algorithm Theoretical Basis Document (i.e. quality_flag = 1, sensitivity >0.9 , and sensitivity $>$ cover; Hofton *et al* 2019). GEDI data from early 2019–mid 2020 were used for analysis.

2.2. Reference data

We used canopy height estimates from the airborne laser scanning (ALS) of the Goddard's airborne LiDAR, Hyperspectral & Thermal Imager (G-LiHT) mission as reference data. Airborne LiDAR Scanning (ALS) instrument has been previously used to validate GEDI (Liu *et al* 2021, Rishmawi *et al* 2021) and ICESat-2 canopy height estimation (Neuenschwander *et al* 2020, Malambo and Popescu 2021, Queinnec *et al* 2021), due to its ability to capture canopy structure complexity with very-fine spatial resolution and high vertical accuracy. G-LiHT adopted high-performance scanning and profiling LiDAR instruments to take waveforms at a diameter of 10 cm and 50 cm, respectively, along continuous transects. G-LiHT yields a basic geometric representation of vegetation and topography where structure can be resolved with very high geolocation accuracy (error < 10 cm) and vertical accuracy (error ≤ 5 cm). The G-LiHT mission also provides 1 m gridded canopy height products (each with a single height above ground) along flight transects (see details in Cook *et al* 2013), which covers diverse landscapes and biomes across North America. This dataset has been widely used to improve forest monitoring (Duncanson *et al* 2014, Masek *et al* 2015, Zhao *et al* 2018). To generate ALS canopy height models, we first selected ALS pixels with canopy height above a threshold, with

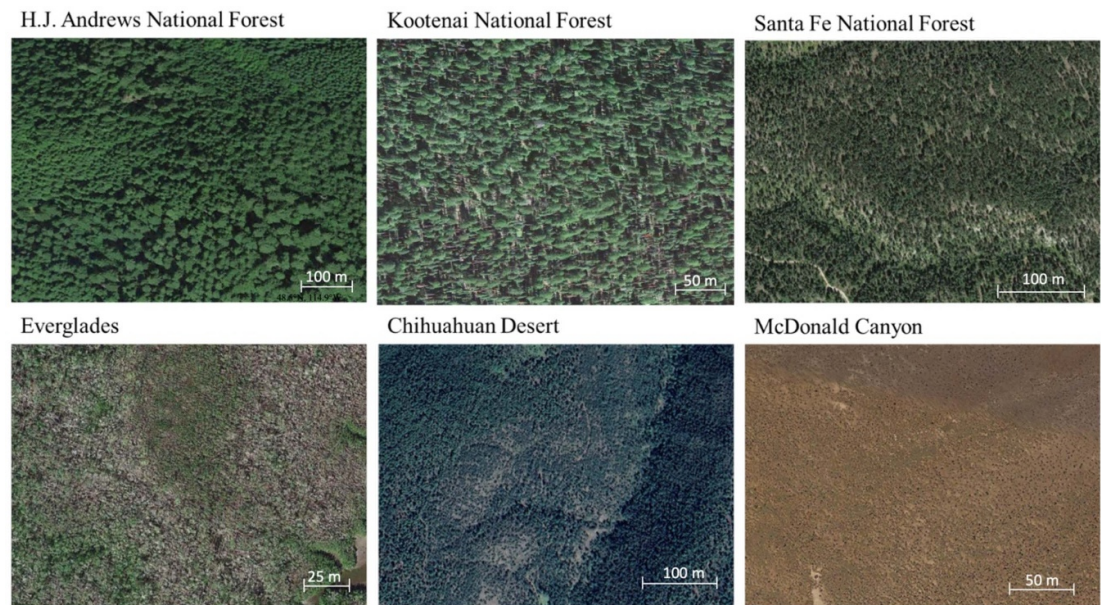


Figure 1. Typical canopy cover for six study sites: 1) Mature dense evergreen needleleaf forest in H.J. Andrews National Forest in Oregon, USA; 2) Mature evergreen needleleaf forest in the Kootenai National Forest in Montana, USA; 3) Dry mixed-species conifer forest in the Santa Fe National Forest, New Mexico, USA; 4) Wetland mangrove forest in Ten Thousand Islands in the Everglades National Park, Florida, USA; 5) Mountainous dryland forest in the Chihuahuan Desert in Chihuahua State, Mexico; 6) Dry shrubland in McDonald Canyon in Arizona, USA. Latitude and longitude for each site is in table 1.

canopies distinguished from ground as height >0.5 m for forest and wetland sites and >0.2 m for dryland sites. We then ordered the ~ 500 (GEDI) or ~ 1300 (ICESat-2) ALS pixels by height and used the values at the different relative height percentiles as the reference relative height.

2.3. Study sites

We choose six study sites from the U.S. and Mexico, representing a range of ecosystems and topography (figure 1) including dense evergreen needleleaf forest (site 1), relatively dry evergreen needleleaf forest (site 2), mesic dry forest (site 3), wetland (site 4), mountain dryland forest (site 5), and flat xeric dryland (site 6). Below we summarize the vegetation characteristics of these sites. Climate, elevation, tree species, canopy cover, reference canopy height and standard deviation, the number of ICESat-2 and GEDI samples, location, and G-LiHT LiDAR sample date are given in table 1. G-LiHT LiDAR reference tree height data was acquired 1–8 years prior to the satellite data for these sites. We examined Google Earth historical satellite photo coverage for the period between airborne and satellite data acquisition for all six sites to ensure that there were no mortality-causing disturbances (fire, insect outbreaks, windstorms, harvesting, other human-caused disturbances) between the airborne and satellite data acquisitions.

2.3.1. Site 1: H.J. Andrews National Forest (dense evergreen needleleaf)

The H.J. Andrews Experimental Forest is located on the western slope of the Cascade Range of Oregon USA about 70 km northeast of Eugene, Oregon. It is a managed forest dominated by closed-canopy evergreen needleleaf species. This area has a Mediterranean climate with cool, wet winters and warm dry summers (Greenland 1994). The topography is steep with deep valleys. Douglas-fir dominates the lower elevations, while silver fir prevails at higher elevations. Since G-LiHT data for this site was acquired in March 2013 (~ 6 – 8 years prior to ICESat2 and GEDI acquisitions), we used a subset of the Experimental Forest covered by old-growth forest where we anticipate slow growth and minimal individual tree death from 2012 to 2019.

2.3.2. Site 2: Kootenai National Forest (evergreen needleleaf)

Located in the Kootenai National Forest in the mountainous terrain of northwestern Montana USA, this site has steep slopes. Sustained by a modified Pacific maritime climate, the Kootenai National Forest harbors mainly Douglas fir, lodgepole pine, spruce-fir, and larch tree species. Like site 1, we chose a subset of the forest covered by old-growth forest to insure little change in tree height between the G-LiHT and satellite measurements.

Table 1. Climate, elevation, tree species, canopy cover, reference canopy height and standard deviation, the number of ICESat-2 and GEDI samples, location, and G-LiHT LiDAR sample date. GEDI and ICESat-2 data for the study were acquired from May 2019 to June 2020.

Site	MAT ^a (°C)	MAP ^a (mm)	Elevation ^b (m)	Tree species	Canopy cover fraction ^c	Terrain slope		Reference Canopy height ^d		Sample count		G-LiHT Sample Date
						Mean (%)	Mean (m)	SD (m)	ICE Sat-2	GEDI	Location	
(1) H.J. Andrews Forest, Oregon, USA	4.4	2500	410–1630	Douglas-fir and silver fir	0.97	34	25.1	14.8	272	536	44.3° N, 122.3° W	March 2013
(2) Kootenai National Forest, Montana, USA	5	700	900–2600	Douglas-fir, lodgepole pine and spruce-fir	0.65	21	12.5	8.6	1406	2522	48.5° N, 114.9° W	August 2012
(3) Santa Fe National Forest, New Mexico, USA	7	600	2040–2700	Pinyon-juniper, Ponderosa pine and Douglas-fir	0.69	22	10.3	7.0	3713	4532	35.9° N, 106.8° W	June 2018
(4) Ten Thousand Islands, Florida, USA	24	1500	0–10	Cypress and mangrove	0.72	4	6.6	4.2	1222	1677	25.9° N, 81.5° W	December 2017
(5) Chihuahuan Desert, Mexico	13.5	350	1800–2500	Pine and oak forest	0.52	19	4.6	3.7	1987	2888	30.1° N, 108.3° W	May 2013
(6) McDonald Canyon, Arizona, USA	13.5	230	1520–1560	N/A	0.07	6	1.0	1.0	48	244	34.9° N, 110.5° W	March 2013

^a MAT and MAP were derived from WorldClim 1 km data (Fick and Hijmans 2017), <https://worldclim.org/data/worldclim21.html>.

^b Elevation is the 30 m digital elevation models from the Shuttle Radar Topography Mission (Rodríguez et al 2006).

^c Canopy cover represents the fraction of the study site covered by canopies, computed as the ratio of ALS 1 m² pixels with canopy height above 0.5 m for forest and wetland and 0.2 m for dryland divided by the total area of the ALS samples.

^d Mean and standard deviation of canopy height represent height statistics at canopy level derived from 1-m ALS canopy height models. With canopy height models, we selected pixels with canopy height above a threshold, with canopies defined by canopy height >0.5 m for forest and wetland sites, and >0.2 m for dryland sites. The threshold was chosen by comparing canopy height models with Google Earth. We randomly selected 100 points for each site and used the 5th percentile as the threshold for canopy height value. Mean and standard deviation of canopy height are the mathematical mean and standard deviation of all the canopy height pixels above the thresholds: 0.5 m for the forest and wetland sites and 0.2 m for the dryland sites.

2.3.3. Site 3: Santa Fe National Forest (mixed-species conifer forest)

Santa Fe National Forest is in northern New Mexico, USA. This site is characterized by a mild, dry climate and rugged topography. Many slow-growing tree species occur, including pinyon pine, juniper, ponderosa pine, Douglas-fir, white fir, and spruce (Lambert 2004).

2.3.4. Site 4: Ten Thousand Islands (wetland mangrove and cypress forest)

Ten Thousand Islands is in southwestern Florida close to the northwestern extent of the Everglades National Park, U.S., with relatively flat topography from sea level to 10 m. The subtropical climate in this region is characterized by mild, dry winters and warm, humid and rainy summers. Dominated by mangrove and cypress, most trees grow on areas separated by open water. While this site is prone to hurricanes, G-LiHT data was collected in December 2017 (three months after Hurricane Irma) with little disturbance prior to ICESat2 and GEDI data acquisitions. Vegetation characteristics were sampled from the vegetated patches only.

2.3.5. Site 5: Chihuahuan Desert (mountainous dryland forest)

This dryland site is in the mountainous Chihuahuan desert, Mexico, 52 km southwest of Nuevo Casas Grandes. Pine and oak forests are found at the higher elevations and grasslands and creosote bush shrublands at the lower elevations.

2.3.6. Site 6: McDonald Canyon (xeric dryland)

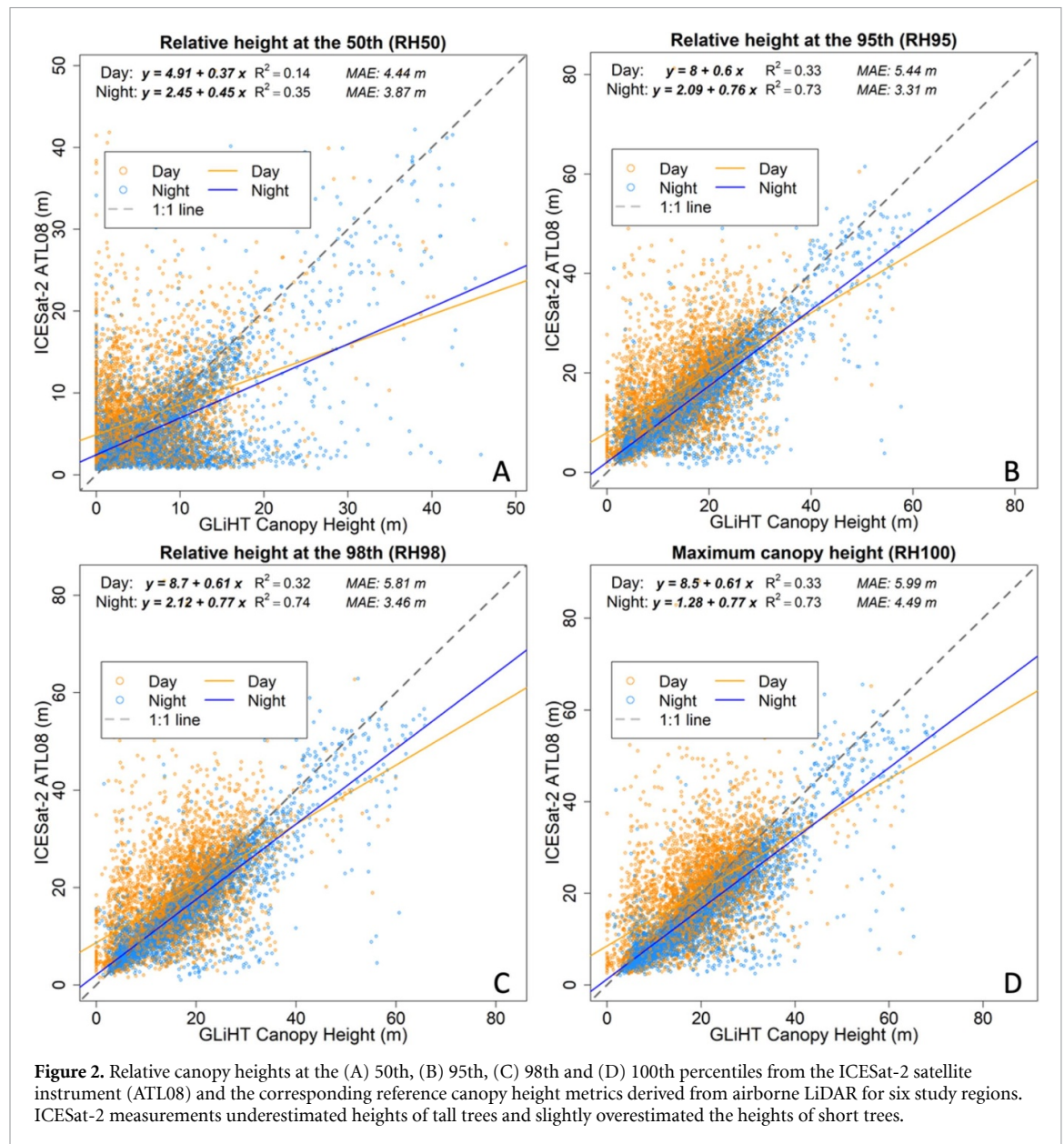
Located in McDonald Canyon southeast of Winslow, Arizona, USA, this site is the driest among the six study sites. This site supports very short sparse shrub canopies with a mean height of ~1 m and low anthropogenic disturbance.

2.4. Height estimation error/uncertainty assessment

G-LiHT data used in this paper were mostly collected during the local growing seasons when tree canopies of deciduous species would normally be in full leaf. G-LiHT data for site 3 was collected in June 2018. G-LiHT flights over sites 1, 2, 5, and 6 were acquired earlier, in late 2012 and early 2013. However, given our deliberate selection of slow growing, low disturbance and old-growth dryland sites and an examination of historical Google Earth historical satellite photo coverage for the period between airborne and satellite data acquisition, we are confident that little change in canopy cover occurred between airborne and satellite data acquisition. The reference data for site 4 was collected in December 2017 after Hurricane Irma and shortly prior to ICESat-2 and GEDI collections in late 2018 and early 2019. Height growth for the old-growth forests at sites 1 and 2 is very slow, as is tree, mangrove/cypress and shrub height growth at sites 3–6.

Reference canopy height metrics, including RH50, RH95, RH98, and RH100, were extracted for GEDI footprints and ICESat-2 segments. A total of 8648 ICESat-2 segments and 12 399 GEDI footprints were obtained across the six study sites. An ICESat-2 segment (of the ATL08 product) covers a rectangular area of 100 m along track and 13 m cross track. Accordingly, reference canopy height metrics from ALS were computed as the corresponding percentiles of the ~1300 1 m² canopy pixels within the spatial extent of each ICESat-2 segment. Similarly, reference metrics for GEDI were calculated with ~500 1 m² canopy pixels from ALS-based canopy height models co-located within the 25 m-diameter circular footprints. To examine whether the error of height estimations is sensitive to canopy cover, we generated the canopy cover fraction for all the ICESat-2 segments and GEDI footprints using the ALS data as the number of 1 m² ALS pixels with a canopy height above 0.5 m for forest and wetland and 0.2 m for dryland divided by the area of individual ICESat-2 segments or GEDI footprints. The geolocation error of ICESat-2 (mean error of 5 m) and GEDI (mean error of 10.2 m) could influence our validation with airborne LiDAR (Roy et al 2021), particularly where the canopy is discontinuous (mangrove site 4), or adjacent patches are different ages from past harvesting. To avoid this issue, we selected areas of old growth (sites 1 and 2) or areas of continuous canopy cover (sites 3–6) for our comparison.

We assessed differences between ICESat-2 or GEDI canopy height estimates and the reference height using mean absolute error (MAE), root mean square error (RMSE), %RMSE (RMSE/mean sample height * 100%) and Bias. We also generated bivariate linear relationships between the estimated canopy height metrics and their corresponding reference metrics. The intercept and slope of the linear models provide estimates of bias and bias sensitivity to vegetation height, respectively, while R-squared values indicate overall goodness-of-fit. Comparison of the linear regression to the 1:1 line provides additional insight into ICESat-2 and GEDI height retrieval bias relative to airborne data.



3. Results

3.1. ICESat-2 canopy height estimation error

We compared four canopy height metrics of night and day ICESat-2 against the corresponding metrics from G-LiHT (figure 2). Our estimates of RMSE, MAE and bias for RH98 show both ICESat-2 and GEDI estimates to be reasonably accurate and unbiased for assessing RH98 across a 1–60 m range of reference canopy heights for all data with RMSE of 7.49 m and 6.52 m, MAE of 4.64 and 4.08 and bias of 0.04 m and 0.09 m for ICESat-1 and GEDI respectively. Both MAE and linear regression models show that night ICESat-2 is more accurate in canopy height retrieval relative to day measurements (RMSE was 9.12 m for day and 5.57 for night and MAE was 5.92 m for day and 3.45 m for night, table 2). The ICESat-2 strong beam gave lower RMSE (6.82 m) and MAE (3.90 m) than the weak beam (RMSE=8.35 m, MAE=5.68 m).

When using ICESat-2 night measurements, RMSE and MAE are lower for RH95 (5.42 m, 3.31 m) and RH98 (5.57 m, 3.45 m) than it is for RH50 (5.91 m, 3.86 m) and RH100 (6.64 m, 4.48 m). The R^2 , slope and intercept of linear models for night measurements is similar for RH95, RH98 and RH100. The linear model for RH50 has a substantially lower R^2 and slope deviating substantially from 1, reinforcing that this ICESat-2 height metric may be of limited value for canopy structure estimates.

For ICESat-2 RH98, height estimation error (the difference between estimated and reference RH98) varies with canopy height, but not with canopy cover or slope (figure 3(A)). Night data is inaccurate for plants <5 m tall (Bias = 3.0 m, 1.4% of total sample), accurate for plants 5–10 m (Bias = −0.29, 6.3% of

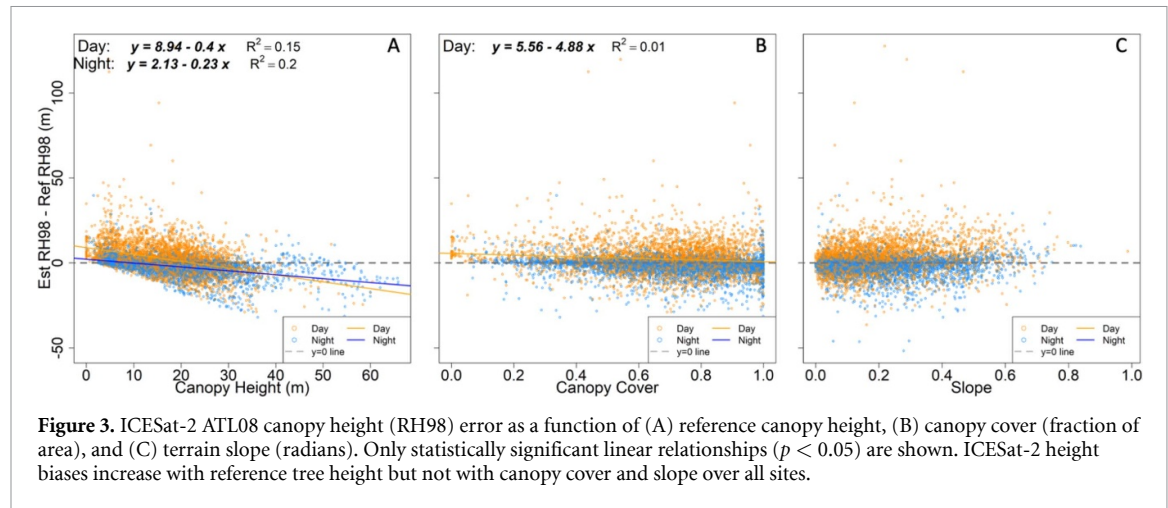
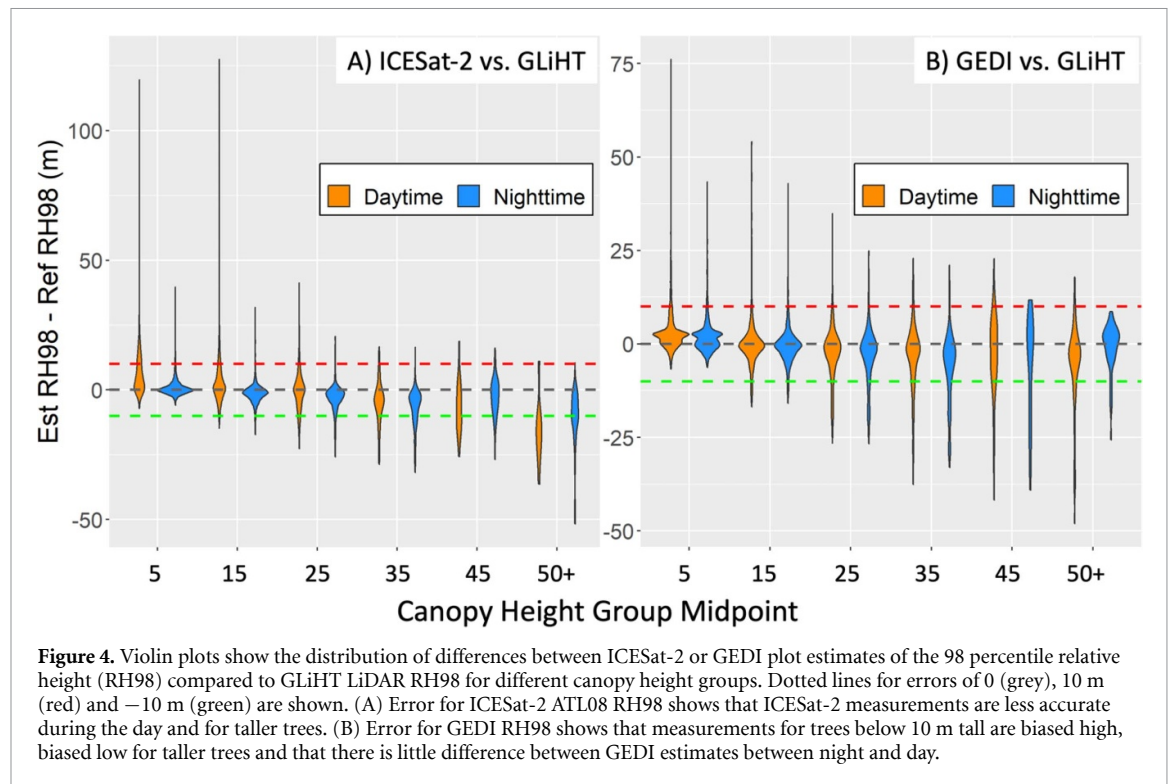


Table 2. Mean sample height, root mean square error (RMSE), %RMSE (RMSE/mean sample height), mean absolute error (MAE) and bias for differences between ICESat-2 or GEDI and G-LiHT relative height at 98 percentile for all data, day or night acquisitions, strong or weak beams (ICESat-2) or power or coverage beams (GEDI), and waveform decomposition algorithms 1 or 2 (GEDI only). Strong (ICESat-2) or Power (GEDI) beams at night yielded the lowest RMSE and MAE, but differences between day and night and power and coverage beams were minor for GEDI estimates. Algorithm 1 gave a lower RMSE and MAE than Algorithm 2, but the mean height for the sample selected for algorithm 1 was also lower.

Comparison	ICESat-2 RH98					GEDI RH98				
	Mean Height (m)	RMSE (m)	%RMSE	MAE (m)	Bias (m)	Mean Height (m)	RMSE (m)	%RMSE	MAE (m)	Bias (m)
All Data	17.5	7.49	43%	4.64	0.04	14.7	6.52	44%	4.08	0.09
Day	16.7	9.12	55%	5.92	2.23	15.9	7.03	44%	4.39	0.02
Night	18.2	5.57	31%	3.45	-2.01	13.5	5.94	44%	3.75	-0.21
Strong/Power Beam	17.5	6.82	39%	3.90	-0.49	14.7	6.52	44%	3.92	0.50
Weak/Coverage Beam	17.4	8.35	48%	5.68	0.77	14.9	6.53	44%	4.27	-0.81
Algorithm 1						13.6	5.26	39%	3.37	-0.73
Algorithm 2						16.6	8.12	49%	5.21	0.92
Day										
Strong/Power Beam	17.0	8.50	50%	4.98	1.01	15.7	7.03	45%	4.16	0.62
Weak/Coverage Beam	16.4	9.83	60%	7.09	3.75	16.2	7.04	44%	4.73	-0.87
Algorithm 1						14.6	5.41	37%	3.47	-0.86
Algorithm 2						18.0	9.07	50%	5.89	1.45
Night										
Strong/Power Beam	18.0	4.99	28%	3.00	-1.75	13.3	5.81	44%	3.61	0.35
Weak/Coverage Beam	18.5	6.38	35%	4.17	-2.42	13.7	6.06	44%	3.89	-0.75
Algorithm 1						12.5	5.09	41%	3.25	-0.59
Algorithm 2						15.1	7.04	47%	4.51	0.38
Sites										
H.J. Andrews, 1	40.5	12.2	30%	7.66	-1.84	39.2	10.9	28%	7.66	-0.10
Kootenai NF, 2	22.9	9.35	41%	5.88	-0.46	20.3	8.65	43%	5.88	1.67
Santa Fe NF, 3	19.8	7.01	35%	3.76	-0.68	17.0	5.66	33%	3.76	0.82
Ten Thousand Islands, 4	11.1	4.29	39%	2.22	-1.45	8.4	2.94	35%	2.22	1.13
Chihuahua, 5	10.4	7.43	71%	3.71	2.72	9.2	6.58	72%	3.71	-2.36
McDonald Canyon, 6	0.4	8.74	2100%	2.89	7.35	0.2	2.98	1880%	2.89	-2.89

total sample), but underestimates canopy height for taller plants (figures 2, 3(A) and 4(A)). The linear fits to the differences between estimates and reference heights for RH98 showed a bias of 0.98 m at 5 m reference height, -3.62 m at 25 m reference height and -9.37 m at 50 m reference height for ICESat-2.

Night errors for ICESat-2 are consistently less than found using day data (figure 4(A)). Canopy cover only influences height estimation errors using day measurements (figure 3(B)). Neither day nor night height errors vary with plot slope (figure 3(C)). Examination of data for each of the six sites (figure S1) shows that performance of ICESat-2 d and night height varies significantly across the six sites, with night being typically more accurate than day estimates, and night estimates are generally better in low- to mid-stature sites. Night estimates with the strong beam had lower RMSE, MAE and Bias than night estimates with the weak beam (table 2).



3.2. GEDI canopy height estimation error

The precision of GEDI relative height estimates was better for night measurements for RH98 (RMSE 5.94 m) compared to day measurements (RMSE 7.03 m), but the mean sample height at night (13.5 m) was also lower than for day (15.9 m), table 2. RMSE for the power beams for RH98 was comparable to that of the coverage beams for both day and night, RMSE was lower for algorithm 1 compared to algorithm 2, but in all cases RMSE varied with mean sample height (table 2). We found no difference in height estimation errors among five 0.02 unit classes for sensitivity >0.9 (figure S8). For our analysis, we separated data by day and night measurements, but used data with both algorithms, both coverage and power beams and sensitivity >0.9 .

Results from our GEDI canopy height assessment indicated better GEDI performance using RH95, RH98 and RH100 with higher error and bias for RH50 (figure 5). The regression slope and intercept indicate best performance for RH95, followed by RH98 and RH100. The MAE of GEDI estimated canopy height is comparable to ICESat-2 night height estimates, but considerably better than ICESat-2 day estimates. Both GEDI and ICESat-2 showed better performance for tall relative height metrics (RH95, RH98, and RH100), with RH50 metrics under-performing for both sensor systems. The differences between GEDI estimates and the reference canopy height vary with canopy height, canopy cover and slope (figure 6), but the trends with canopy cover and slope are minor. The linear fits to the differences between estimates and reference heights for RH98 (figure 5) showed a bias of 2.14 m at 5 m reference height, -2.47 m at 25 m reference height and -8.22 m at 50 m reference height for GEDI. GEDI estimates for reference height <5 m are strongly biased (Bias = 3.6 m) because of a consistent cutoff at $\sim 2\text{--}4$ m across all the sites (figure S2) and underestimates the height of trees >20 m (figures 4(B) and 6). For individual study sites, the Chihuahuan desert (site 5) and the mixed-species conifer forest (site 3) height comparisons showed a positive bias with increasing slope together with an $R^2 > 0.01$ (figure S7). Relationships of height errors and slope for the other 4 sites were either not present or had $R^2 < 0.02$.

4. Discussion

This study examined the quality of the GEDI and ICESat-2 canopy height products in ecosystems characterized by different vegetation structure and topography. GEDI and night ICESat-2 datasets provide canopy height estimates with comparable accuracy. Both products underestimate the height of taller trees, had Bias >3 m for reference heights of <5 m and were ineffective for the <1 m heights of the driest site. Both GEDI and ICESat-2 showed better estimation for upper canopy height metrics (RH95, RH98 and RH100) than for RH50. Height estimates of both ICESat-2 and GEDI are insensitive to terrain slope and canopy cover in this study which was conducted across six sites with considerable variability in canopy cover and slope

(ranging 7%–97% average cover and 4%–34% average slope, table 1). Overall, GEDI has slightly higher accuracy for estimating canopy height than ICESat-2.

4.1. Variation of canopy height estimation with tree height and day or night sampling

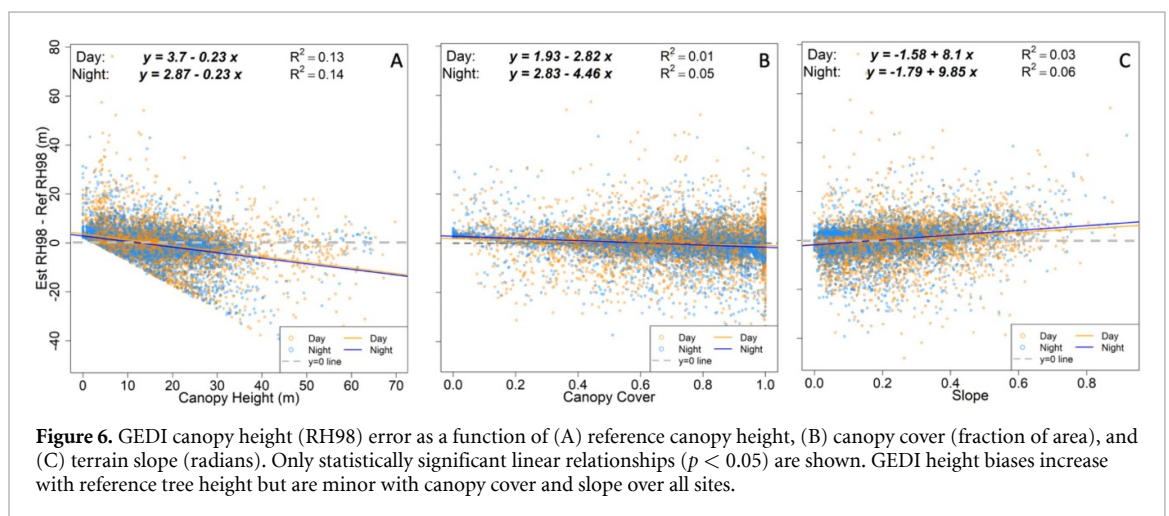
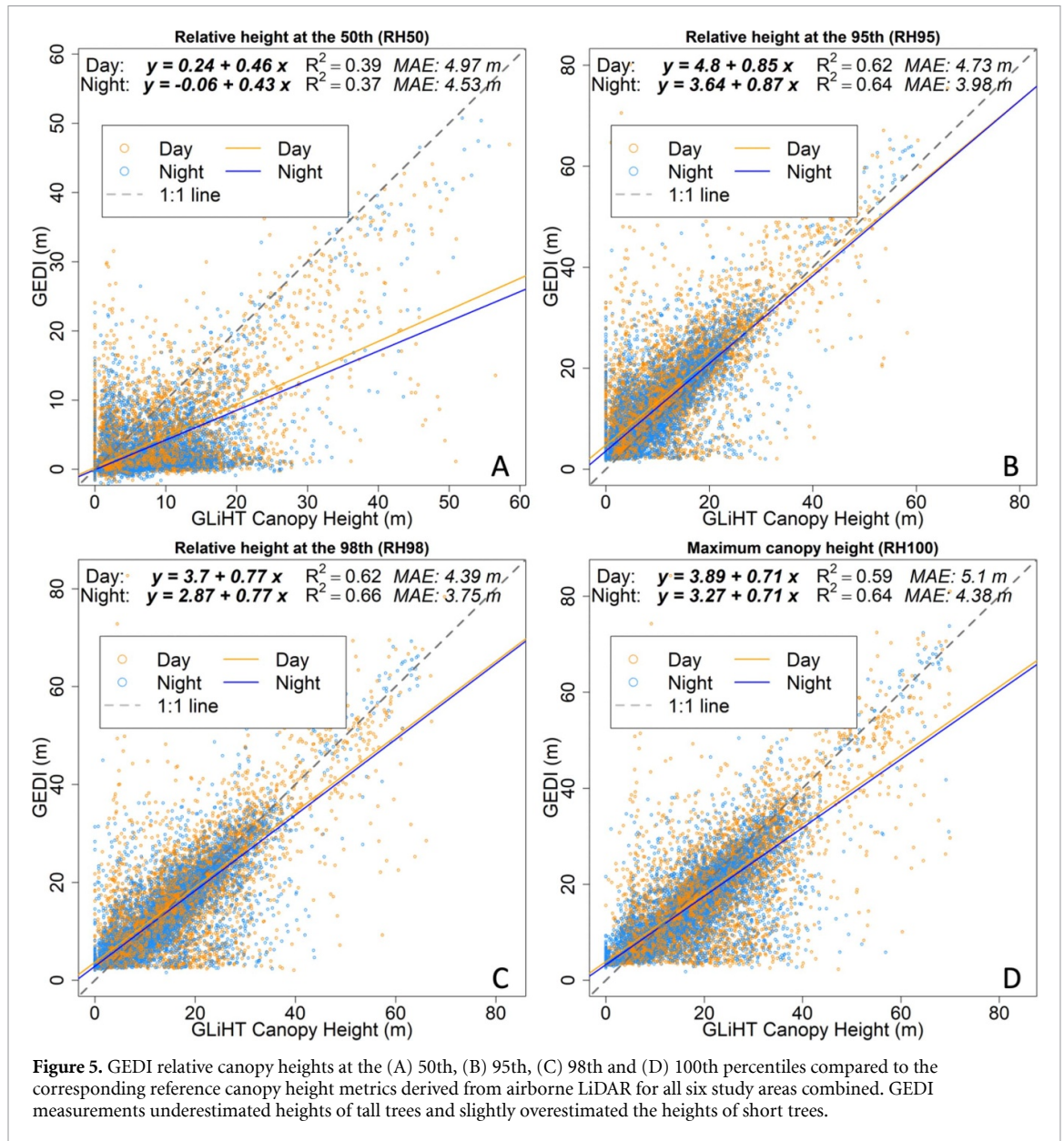
This study found height estimate accuracy based on RMSE and Bias (table 2) comparable to those of other studies for both ICESat-2 and GEDI (ICESat-2: Liu *et al* 2021, Malambo and Popescu 2021, GEDI: Adam *et al* 2020, Liu *et al* 2021, Fayad *et al* 2021a, 2021b, Kutchartt *et al* 2022, Wang *et al* 2022), though most of these found less of a height bias than found here perhaps because the overall height range was smaller for earlier studies. Other assessments of ICESat-2 also showed the importance of restricting samples to night estimates for height (Liu *et al* 2021, Malambo and Popescu 2021).

Our study found that ICESat-2 and GEDI canopy heights for reference canopy height <5 m were ineffective and both instruments underestimated canopy heights for taller trees (>25 m; figures 2, 3, 5 and 6). Other GEDI and ICESat-2 assessments found similar biases, but not all. In a study across a wide range of biomes in NEON sites, Wang *et al* (2022) found bias ranged from −0.24 to −4.69 for RH100 for NEON forested sites with GEDI. Adam *et al* (2020) showed that GEDI overestimated RH100 by ~5 m for <20 m tall canopies, with bias decreasing to ~1 m for canopies >30 m. In a different comparison over NEON sites, Liu *et al* (2021) found that overall bias for RH100 was 0.77 m for ICESat-2 and −0.79 m for GEDI (night + day acquisitions) and −0.87 m for ICESat-2 and −0.18 m for GEDI (night acquisitions, with strong beam for ICESat-2 and power beam for GEDI). Bias with reference canopy height appeared to decrease for both ICESat-2 and GEDI for the Liu *et al* (2021) study when using night measurements and strong or power beams only (our interpretation of their figures 5 and 6). Malambo and Popescu (2021) showed an ICESat-2 RH98 negative bias of −5% to −40% for mostly forested sites and a positive bias for RH98 of 20%–50% for chaparral vegetation and for tropical and subtropical areas with grasslands and scattered trees. Kutchartt *et al* (2022) found that GEDI underestimated canopy heights by ~3 m in high canopy cover with taller trees and underestimated canopy heights by ~3 m in low canopy cover with shorter trees. In a wet tropical forest, GEDI estimate of RH100 for a reference height >30 m was 24.4 m using the coverage beams, 32.1 m with the full-power beams, and 36.7 m with the LVIS (Fayad *et al* 2022). With data presented in many of these studies, it is difficult to assess the importance of any bias with tree height as canopy height is often unreported.

Both ICESat-2 and GEDI showed better performance using relative height metrics of 95 percentile or greater. ICESat-2, particularly the night data, severely underestimates median canopy height (RH50). Because the relative height metrics are estimated as the percentiles of the cumulative distribution of canopy height above the estimated ground surface, underestimation of RH50 may be caused by scattered photons from ground mis-identified as canopy photons (figure S4). GEDI also underestimates RH50, which is likely due to the mixture of ground returns with canopy returns. For example, in figure S5 canopy returns were considered as ground, which leads to the underestimation of RH50 (7 m), comparing to the reference RH50 (15 m).

GEDI and ICESat-2 bias likely arises from the difficulty in distinguishing ground and canopy signals. However, instead of the challenge for canopy top detection faced by ICESat-2, the bias in GEDI is more likely derived from detecting ground returns in the denser canopies with taller trees. GEDI adopted an approach based on Gaussian Decomposition to differentiate ground and canopy, which decomposes the waveform return into a series of components assuming the position of each component represents the structure of ground objects (Hofton *et al* 2019). For footprints with high-cover tall plants, ground signals can be easily mixed with canopy returns and result in wide ground waveforms. For example, in the footprint with relatively high canopy cover illustrated in figure S5, the distance from RH0 to the detected ground can be as high as 8.6 m. In this case, Gaussian decomposition, which assigns the center of the lowest peak as ground, intrinsically considers canopy returns as ground and thus underestimates canopy height. For low-cover low-stature sites, GEDI shows consistently larger canopy height estimation (Site McDonald Canyon in figures S2 and 5). For example, the lowest RH98 by GEDI is about 2.2 m in McDonald Canyon (figure S2), where the median top of canopy height is about 1 m (table 1). This constant overestimation could be a result of the broad ground distribution of GEDI waveforms. The ground distribution at low-cover low-stature footprints shows a 3–4 m upper shoulder (figure S6), which leads to a canopy height estimation cutoff. The cutoff on height estimation is very likely due to the light pulse width of GEDI instrument: 15.6 ns, which could lead to the mixture of returns from objects close to ground. Thus, GEDI's pulse width poses challenges to height retrieval of short shrubs.

Accurate canopy height estimation using LiDAR relies on the ability to distinguish canopy elements (branches and leaves) from a complex return signal that also includes the surface and noise. For the ICESat-2 instrument, the noise component includes solar background photons and instrument noise (Brenner *et al* 2018). Identifying and removing noise photons is thus the most critical step of ICESat-2 canopy height estimation. ICESat-2 ATL08 adopted an approach based on photon density, where photons are classified as signal in regions of higher density (Neuenschwander and Pitts 2019). In areas of low stature and low cover



vegetation, few photons returned from the canopy make it more challenging to differentiate canopy photons from background photons. As a result, ICESat-2, especially the day data with higher level of solar background photons (figure S3), can overestimate canopy height for heights $< \sim 20$ m (figure 2). While the night data is

less affected by solar background, the noise filtering algorithm tends to mistakenly classify the top of canopy photons as noise, and thus leads to underestimation of canopy height for tall plants (figure S4).

4.2. Variation of canopy height estimation slope, canopy cover, beam type and algorithm

In contrast to other studies, slope had only a slight impact on GEDI height estimation while ICESat-2 heights were unrelated to slope. These results likely arise because ground detection may be easier for ICESat-2 because of its elongated (~100 m) data sampling and aggregation strategy (Neuenschwander *et al* 2020, figure S3). Several studies found that ICESat-2 or GEDI height estimates were biased in samples with steep slopes (ICESat-2: Liu *et al* 2021, GEDI: Adam *et al* 2020, Liu *et al* 2021, Fayad *et al* 2021a, Kutchartt *et al* 2022, Wang *et al* 2022). For GEDI, the ground estimation for GEDI waveforms could be broadened in steep terrain where canopy returns are gradually mixed with the ground returns (Wang *et al* 2019, Yang *et al* 2011a), leading to potential overestimation of canopy height (figure 7 in Wang *et al* 2019). Because terrain slope for this study was derived from Shuttle Radar Topographic Mission data (Rodriguez *et al* 2006) with a 30 m resolution, this data may not have been precise enough to identify a slope effect compared to slope derived from airborne LiDAR used in the studies that found an effect.

Future studies should work to reduce the impact of slope on GEDI canopy height estimation (Fayad *et al* 2021a). Terrain effect on the signal from large footprint LiDAR has been discussed and investigated and two types of methods have been proposed: Gaussian decomposition (Chen 2010, Lee *et al* 2011, Næsset *et al* 2013) and the integration of waveform parameters and terrain characteristics (Lefsky *et al* 2005, 2007, Lefsky 2010, Xing *et al* 2010, Gwenzi and Lefsky 2014). Processing GEDI waveforms with their smaller footprint could benefit from these approaches.

Canopy cover had little impact on height estimate errors for ICESat-2 and GEDI for this study and for Kutchartt *et al* (2022), in contrast with other studies that showed biased estimates or increases in error with canopy cover (Adam *et al* 2020, Dorado-Roda *et al* 2021, Liu *et al* 2021, Malambo and Popescu 2021, Lahssini *et al* 2022, Wang *et al* 2022). Dense canopy cover will decrease the probability of photons reaching the ground for ICESat-2 and broaden or complicate the apparent ground peak return for GEDI (figures S5 and S6). We are uncertain as to why this study found no bias with canopy cover for ICESat-2 and GEDI while some other studies did.

This study found differences between ICESat-2's strong and weak beams at night, with lower error and bias for the strong beams. These results are comparable to those found in a cross-NEON assessment (Liu *et al* 2021), but another cross-USA study found that the weak beam samples had lower bias, but higher error than did the strong beam samples (Malambo and Popescu 2021). We found little difference between error or bias for the power and coverage beams for GEDI in this study, in agreement with one assessment (Rajab-Pourrahmati *et al* 2023), but not others (Adam *et al* 2020, Liu *et al* 2021, Fayad *et al* 2022, Kutchartt *et al* 2022, Lahssini *et al* 2022, Wang *et al* 2022). Differences in GEDI height errors between Algorithms 1 and 2 were confounded with differences in the mean height of the sample for each Algorithm, and we can draw no information from the performance of two Algorithms selected in waveform processing.

Previous research has suggested that geolocation error is also a significant source of canopy height error, especially for GEDI (Dubayah *et al* 2020a, Potapov *et al* 2021, Roy *et al* 2021). We did not evaluate the impact of geolocation error on canopy height estimation, focusing instead on sites with large, uniform patches. Geolocation error could have stronger influence at footprint level height estimation for areas with more spatial variability in tree heights. Lang *et al* (2022) and Hancock *et al* (2019) have provided some approaches to correct geolocation error of GEDI. These techniques rely on assessing the best fit of the GEDI metrics to airborne LiDAR estimates within the uncertainty area of the GEDI footprint, which may introduce bias.

4.3. Uncertainties and limitations in the study

The time between airborne LiDAR and ICESat-2 or GEDI measurements is the largest uncertainty in this study, with 6–8 year difference between G-LiHT acquisitions and ICESat-2 and GEDI acquisitions except for the mixed species and mangrove-cypress forests (sites 3 and 4, 1–3 years). For sites with the longest gap between airborne and satellite acquisitions, we selected slow growing, low disturbance old-growth and dryland sites. Height growth for the old-growth forests at sites 1 and 2 is very slow, as is tree, mangrove/cypress and shrub height growth at sites 3–6. We examined historical Google Earth satellite photo coverage for the period between airborne and satellite data acquisition to ensure that there were no mortality-causing disturbances (fire, insect outbreaks, windstorms, harvesting, other human-caused disturbances) between the airborne and satellite data acquisitions. The reference data for site 4 was collected in December 2017 after Hurricane Irma and shortly prior to ICESat-2 and GEDI collections in late 2018 and early 2019. We are confident that no large disturbance and little canopy growth occurred at our study sites between the airborne and satellite measurements.

Another limitation of this (and all ICESat-2 and GEDI assessment studies) is the large number of substantial outliers in the satellite datasets. Future work on developing and testing methods for outlier removal would benefit users of ICESat-2 and GEDI data.

4.4. Recommendations and future improvements

The research assessed canopy height estimation by ICESat-2 and GEDI using airborne LiDAR data, and examined the impacts of canopy height, canopy cover, terrain slope, and acquisition time on canopy height estimation. Our research showed comparable accuracy of ICESat-2 and GEDI in different biomes, demonstrating the strengths and limits of their use.

Assessing the performance of spaceborne LiDARs across a range of site conditions (with different ranges of terrain slopes, canopy cover and vegetation heights) and comparing different studies using only error metrics (RMSE, MAE, Bias) is problematic. These metrics are only correct for the sample from which they were calculated and cannot identify bias and error for factors not included in the analysis. For example, our estimates of RMSE, MAE and bias for RH98 show both ICESat-2 and GEDI estimates to be reasonably accurate and unbiased for assessing RH98 across a 1–60 m range of reference canopy heights with RMSE of 7.49 m and 6.52 m, MAE of 4.64 and 4.08 and bias of 0.04 m and 0.09 m for ICESat-1 and GEDI respectively. The GEDI sample has 2.8 m lower mean tree height than the ICESat-2 sample which could influence the RMSE and MAE. None of the statistics offer clues to the strong biases our study found with increasing tree height for both sensors, or to the differences between night and day acquisitions and strong and weak beams for ICESat-2.

Based on our analysis of the errors and uncertainties associated with ICESat-2 and GEDI height estimation, we offer recommendations for future data processing. First, for both ICESat-2 and GEDI, RH98 is better than RH100 for estimating canopy top, while mid-canopy RH50 had high error and bias. Second, ICESat-2 night data, perhaps with the strong beam only, is a better choice over data from day acquisitions. Third, neither ICESat-2 nor GEDI canopy height products have the accuracy to measure the height of low-stature shrubs and short trees (<5 m). GEDI pulse width currently limits retrieval of low-cover low-stature shrub heights, with a consistent ~2–4 m minimum retrieval height, while ICESat-2 data for <5 m is noisy and biased toward overestimation. Fourth, while not a major factor in our analysis, based on our review of other assessment studies corrections for slope bias should be considered when using GEDI and ICESat-2 night data. Fifth, methods should be developed and tested for outlier removal. Finally, both ICESat-2 and GEDI have highly variable accuracy among individual samples. Because of this variability, it may be more appropriate to use the statistics of canopy height over large plots rather than relying on data from individual samples.

Data availability statement

No new data were created or analyzed in this study. The data subset from GEDI and ICESat-2 used in this study is available by request to the corresponding author.

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CORRIGENDUM

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Corrigendum: Assessing canopy height measurements from
ICESat-2 and GEDI orbiting LiDAR across six different biomes with
G-LiHT LiDAR (2024 *Environ. Res.: Ecology* **3** 025001)Qiuyan Yu¹, Michael G Ryan^{2,*} , Wenjie Ji³, Lara Prihodko⁴, Julius Y Anchang¹, Njoki Kahiu¹ ,
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Table 2 of the original paper had incorrect values for the mean absolute error (MAE) for ICESat-2 for the six
individual study sites. The correct values are given below.

Table 2. Mean sample height, root mean square error (RMSE), %RMSE (RMSE/mean sample height), mean absolute error (MAE) and Bias for differences between ICESat-2 or GEDI and G-LiHT relative height at 98 percentile for all data, day or night acquisitions, strong or weak beams (ICESat-2) or power or coverage beams (GEDI), and waveform decomposition algorithms 1 or 2 (GEDI only). Strong (ICESat-2) or Power (GEDI) beams at night yielded the lowest RMSE and MAE, but differences between day and night and power and coverage beams were minor for GEDI estimates. Algorithm 1 gave a lower RMSE and MAE than algorithm 2, but the mean height for the sample selected for algorithm 1 was also lower.

Comparison	ICESat-2 RH98						GEDI RH98					
	Mean Height (m)	RMSE (m)	%RMSE	MAE (m)	Bias (m)		Mean Height (m)	RMSE (m)	%RMSE	MAE (m)	Bias (m)	
All Data	17.5	7.49	43%	4.64	0.04		14.7	6.52	44%	4.08	0.09	
Day	16.7	9.12	55%	5.92	2.23		15.9	7.03	44%	4.39	0.02	
Night	18.2	5.57	31%	3.45	−2.01		13.5	5.94	44%	3.75	−0.21	
Strong/Power Beam	17.5	6.82	39%	3.90	−0.49		14.7	6.52	44%	3.92	0.50	
Weak/Coverage Beam	17.4	8.35	48%	5.68	0.77		14.9	6.53	44%	4.27	−0.81	
Algorithm 1							13.6	5.26	39%	3.37	−0.73	
Algorithm 2							16.6	8.12	49%	5.21	0.92	
Day												
Strong/Power Beam	17.0	8.50	50%	4.98	1.01		15.7	7.03	45%	4.16	0.62	
Weak/Coverage Beam	16.4	9.83	60%	7.09	3.75		16.2	7.04	44%	4.73	−0.87	
Algorithm 1							14.6	5.41	37%	3.47	−0.86	
Algorithm 2							18.0	9.07	50%	5.89	1.45	
Night												
Strong/Power Beam	18.0	4.99	28%	3.00	−1.75		13.3	5.81	44%	3.61	0.35	
Weak/Coverage Beam	18.5	6.38	35%	4.17	−2.42		13.7	6.06	44%	3.89	−0.75	
Algorithm 1							12.5	5.09	41%	3.25	−0.59	
Algorithm 2							15.1	7.04	47%	4.51	0.38	
Sites												
H.J. Andrews, 1	40.5	12.2	30%	8.99	−1.84		39.2	10.9	28%	7.66	−0.10	
Kootenai NF, 2	22.9	9.35	41%	5.91	−0.46		20.3	8.65	43%	5.88	1.67	
Santa Fe NF, 3	19.8	7.01	35%	4.77	−0.68		17.0	5.66	33%	3.76	0.82	
Ten Thousand Islands, 4	11.1	4.29	39%	2.49	−1.45		8.4	2.94	35%	2.22	1.13	
Chihuahua, 5	10.4	7.43	71%	4.16	2.72		9.2	6.58	72%	3.71	−2.36	
McDonald Canyon, 6	0.4	8.74	2100%	7.35	7.35		0.2	2.98	1880%	2.89	−2.89	

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