GEDI_Gridded_ALS_validation

We used high-resolution gridded ALS to validate select 1 km and 6 km gridded GEDI metrics. We used the following ALS datasets: (1) NEON, USA (2) Sonoma County, CA, USA (3) Coconino National Forest, AZ, USA (4) NASA CMS Indonesia (Melendy et al. 2014), (5) EFForTS Indonesia (Camarretta et al. 2021; Schlund et al. 2023), and (6) SAFE Malaysia (Swinfield et al. 2020). For the NEON dataset, we validated canopy height (RH98), height of median energy (RH50), total plant area index (PAI), and foliage height diversity (FHD). See the dataset landing page for plots associated with the NEON validation. For the other five regions we validated canopy height (RH98) at a minimum, and in some cases (when other gridded ALS metrics were already available) we validated additional metrics (Table 1). We report the following validation statistics:

- adjusted R squared (R^2) from a linear model of the form ALS ~ GEDI
- Root mean squared error (RMSE)
- Relative RMSE = 100 * (RMSE / mean(ALS))
- Mean absolute error (MAE)

Table 1. Summary of ALS datasets used for validation.

Dataset name	Country, State	ALS Acquisition Dates	ALS pixel size	GEDI Metrics Validated	ALS Data Access
1. NEON	USA, Multiple States	June-Sept. 2020-2021	1 m	RH98, RH50, PAI, FHD	https://data.neonscience.org/data-products/DP1.30003.001
2. Sonoma County	USA, California	Sept. 28 - Nov. 26, 2013	3 m	RH98	https://sonomavegmap.org/data-downloads/
3. Coconino NF	USA, Arizona	Aug. 16 - 20, 2019	1 m	RH98	https://doi.org/10.3334/ORNLDAAC/1540
4. NASA CMS	Indonesia, Kalimantan	Oct. 18 - Nov. 30, 2014	3 m	RH98	https://doi.org/10.3334/ORNLDAAC/1540
5. EFForTS	Indonesia, Jambi	Jan. 24 - Feb. 5, 2020 and Nov. 21 - 24, 2022	1 m for RH98; 10 m otherwise	RH98, RH50, PAI, FHD	https://doi.org/10.25625/CKLY7X, https://doi.org/10.25625/HWTBW5
6. SAFE	Sabah, Malaysia	Nov. 2014	1 m for RH98; 10 m otherwise	RH98, PAI, FHD	https://zenodo.org/doi/10.5281/zenodo.4020696

1. NEON validation

The 1 km gridded GEDI product was validated with National Ecological Observation Network (NEON) ALS data across a large range of latitudes and longitudes throughout the United States (NEON 2021). First, we downloaded all ALS point cloud tiles for 31 NEON sites with >30% forest cover. We queried all ALS tiles between 2020-2021, selecting the year with the best spatial coverage (tiles *n*), and where tied, selected the most recent year, resulting in approximately 1.5 TB of ALS across all sites. Second, we normalized all point clouds by tile using the 'lidR' package (Roussel and Auty 2019) in R (R Core Development Team 2021). This process entailed instituting a multi-step noise removal algorithm consisting of (a) employing an isolated voxels filter that removes all 1 m voxels filter with fewer than 3 pts/m^2; (b) determining the ground surface by estimating a digital terrain model (DTM) by interpolating a convex hull from all points classified as ground and removing all negative values; and (c) normalizing all point heights (z values) by subtracting the DTM from all points, and removing all negative values.

Third, we determined a RH98 canopy height model (CHM) at 1 m spatial resolution as the 98^{th} percentile of all points/m^2. Concurrently, we generated a 25 m PAI raster by calculating plant area density for 25 m pixels using a universal extinction coefficient in the "leafR" package in R (Almeida et al. 2021). Fourth, we aligned all ALS rasters with corresponding gridded GEDI data by: (a) mosaicking all 1 m RH98 CHMs and 25 m PAI rasters across each NEON site; (b) masking water and urban classes from each ALS raster based on the 2019 National Land Cover Database (NLCD) (Dewitz et al. 2019); (c) projecting and resampling all ALS mosaics to match those from gridded GEDI; (c) aggregating 1 m and 25 m rasters to 1 km by mean, median, standard deviation, interquartile range, 95th percentile, and Shannon's H; and (d) trimming all edge pixels so that only GEDI and ALS mosaic pixels with 100% overlap (i.e. "core" pixels) were retained. Finally, for validation, we extracted all co-located ALS and GEDI pixels and assessed accuracy via root mean squared error (RMSE), relative RMSE, mean absolute error (MAE) and adjusted R^2 (Wu et al. 2019). The mean (across all NEON sites) of each validation statistic is shown in Table 2.

Table 2. The mean (across all NEON sites) of each validation statistic (RMSE, Rel. RMSE, MAE, and Adj. R^2) for each GEDI metric and aggregation statistic at 1 km spatial resolution.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples
RH98	Mean	3.35	0.24	2.43	0.91	3515
RH98	Median	3.88	0.28	2.69	0.89	3515

RH98	SD	2.21	0.45	1.51	0.69	3515
RH98	IQR	4.06	0.60	2.70	0.61	3515
RH98	95th Perc.	5.03	0.23	3.07	0.87	3515
RH98	Shannon’s H	0.39	0.26	0.29	0.68	3515
RH50	Mean	2.43	0.43	1.62	0.90	3515
RH50	Median	2.90	0.54	1.77	0.88	3515
RH50	SD	1.57	0.51	1.12	0.73	3515
RH50	IQR	3.12	0.75	2.03	0.60	3515
RH50	95th Perc.	3.92	0.36	2.66	0.85	3515
RH50	Shannon’s H	0.59	0.42	0.44	0.67	3493
PAI	Mean	0.59	0.57	0.40	0.82	3515
PAI	Median	0.66	0.65	0.43	0.79	3515
PAI	SD	0.67	1.57	0.53	0.33	3515
PAI	IQR	0.93	1.60	0.63	0.30	3515
PAI	95th Perc.	1.65	0.94	1.25	0.57	3515
PAI	Shannon’s H	0.64	0.43	0.50	0.53	3515
FHD	Mean	0.56	0.29	0.42	0.88	3515
FHD	Median	0.64	0.33	0.45	0.85	3515

FHD	SD	0.23	0.45	0.17	0.46	3515
FHD	IQR	0.48	0.71	0.30	0.40	3515
FHD	95th Perc.	0.48	0.18	0.32	0.83	3515
FHD	Shannon’s H	0.57	0.23	0.40	0.19	3515

2. Other ALS validation

We made use of other readily available ALS datasets in the USA and Southeast Asia. Canopy height models, and in some cases other gridded metrics, were distributed with some ALS datasets, specifically NASA CMS, EFForTS, and SAFE (Table 5). These metrics were computed with commonly used packages like leafR (Almeida et al. 2021), lidR (Roussel et al. 2019), and PDAL (Butler et al. 2021; PDAL Contributors 2022). For Coconino NF we computed a high spatial resolution canopy height model by subtracting a digital surface model from a digital terrain model, both computed using PDAL. We uploaded the high-resolution ALS rasters along with associated gridded GEDI rasters to Google Earth Engine (Gorelick et al. 2017) where we developed a validation script.

Similar to the steps described for NEON validation, we used a combination of masks to ensure a fair comparison between ALS and GEDI at spatial resolutions greater than or equal to 1 km. First we identified heavily urban or surface water pixels since these areas are not relevant for validation. For the USA, we used NLCD 2021 land cover (Dewitz 2023) to determine urban and surface water pixels. For Southeast Asia, we used the mean GLAD annual surface water percentage (Pickens et al. 2020) and urban classification from Copernicus Global Land Service 100 m Land Cover to define water and urban masks (Buchhorn et al. 2020). Furthermore, considering the forest structure dynamics (especially in Southeast Asia) we added a mask to identify pixels which had a stand-replacing disturbance (Hansen et al. 2013) during the year of or after the primary ALS acquisition year. We combined these three masks together to summarize the valid percent of each gridded pixel (i.e. not surface water, not urban, and not disturbed). In order for a gridded pixel to be eligible for validation we required that at least 90% of the 30 m pixels used to determine the combined mask be valid. For each valid 1 km or 6 km pixel we computed the mean, median, standard deviation, interquartile range, 95th percentile, and Shannon’s H of the ALS raster which had been resampled to 25 m to match the GEDI footprint diameter. We extracted the corresponding ALS and GEDI gridded values for each metric, aggregation statistic, and pixel. We exported the resulting table to R and produced scatter plots and summary statistic tables.

a. Sonoma County, CA, USA

ALS data were acquired for Sonoma County, CA, USA in 2013. We used a 3 m spatial resolution canopy height model for validation. Given the large extent of the County, we performed validation at 1 km and 6 km spatial resolution. Note that there is at least 6 years between ALS and GEDI lidar acquisition, so some error may be attributable to growth and/or non-stand-replacing disturbances.

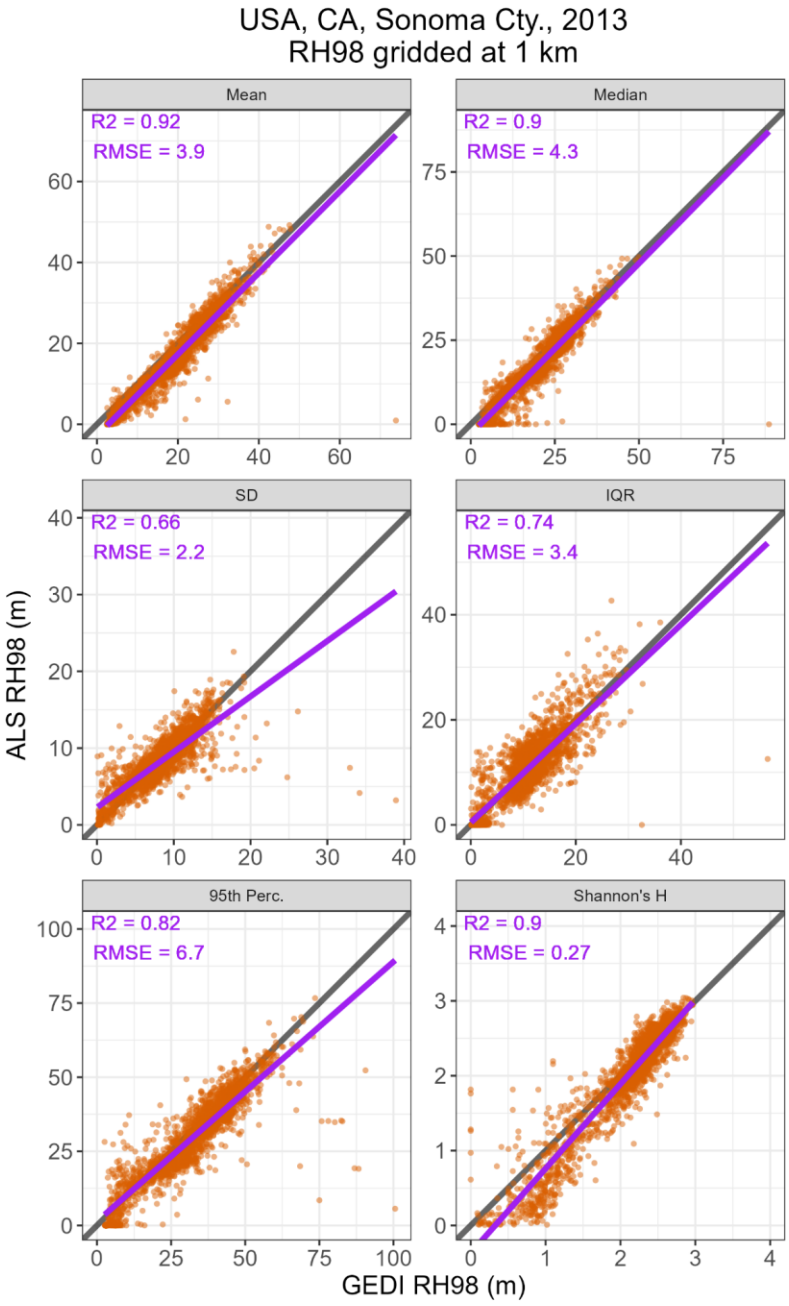

Figure 1. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line

has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

Table 3. Summary statistics for Sonoma County 1 km validation.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples
RH98	Mean	3.9	26.0	3.0	0.92	2262
RH98	Median	4.3	29.8	3.2	0.90	2262
RH98	SD	2.2	26.6	1.3	0.66	2262
RH98	IQR	3.4	33.0	2.5	0.74	2262
RH98	95th Perc.	6.7	23.2	4.4	0.82	2262
RH98	Shannon's H	0.3	13.6	0.2	0.90	2233

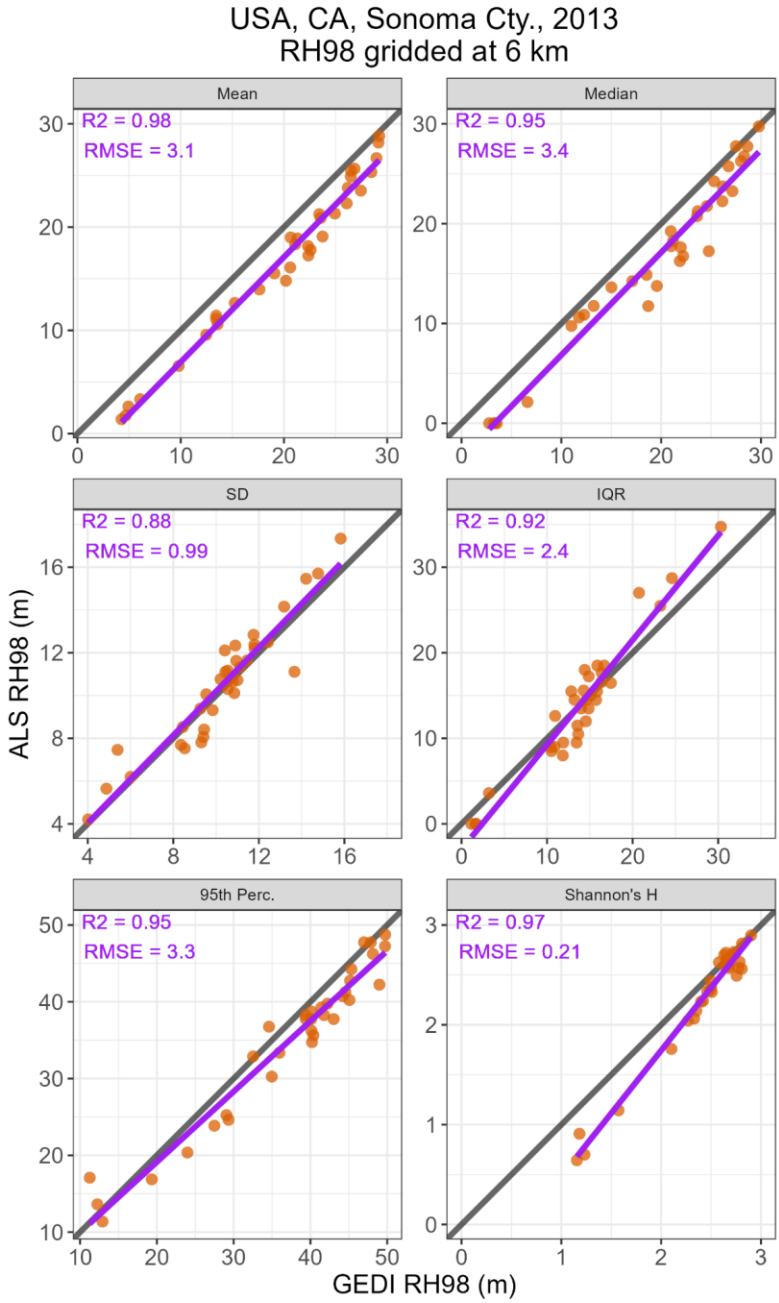

Figure 2. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 6 km cells.

Table 4. Summary statistics for Sonoma County 6 km validation.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples

RH98	Mean	3.1	18.4	2.9	0.98	34
RH98	Median	3.4	20.9	2.9	0.95	34
RH98	SD	1.0	9.4	0.8	0.88	34
RH98	IQR	2.4	17.5	2.0	0.92	34
RH98	95th Perc.	3.3	9.6	2.9	0.95	34
RH98	Shannon's H	0.2	9.1	0.2	0.97	34

b. Coconino National Forest, AZ, USA

ALS data were acquired for Coconino National Forest, AZ, USA in 2019. We computed a 1 m spatial resolution canopy height model for validation. Given the large extent of the National Forest, we performed validation at 1 km and 6 km spatial resolution.

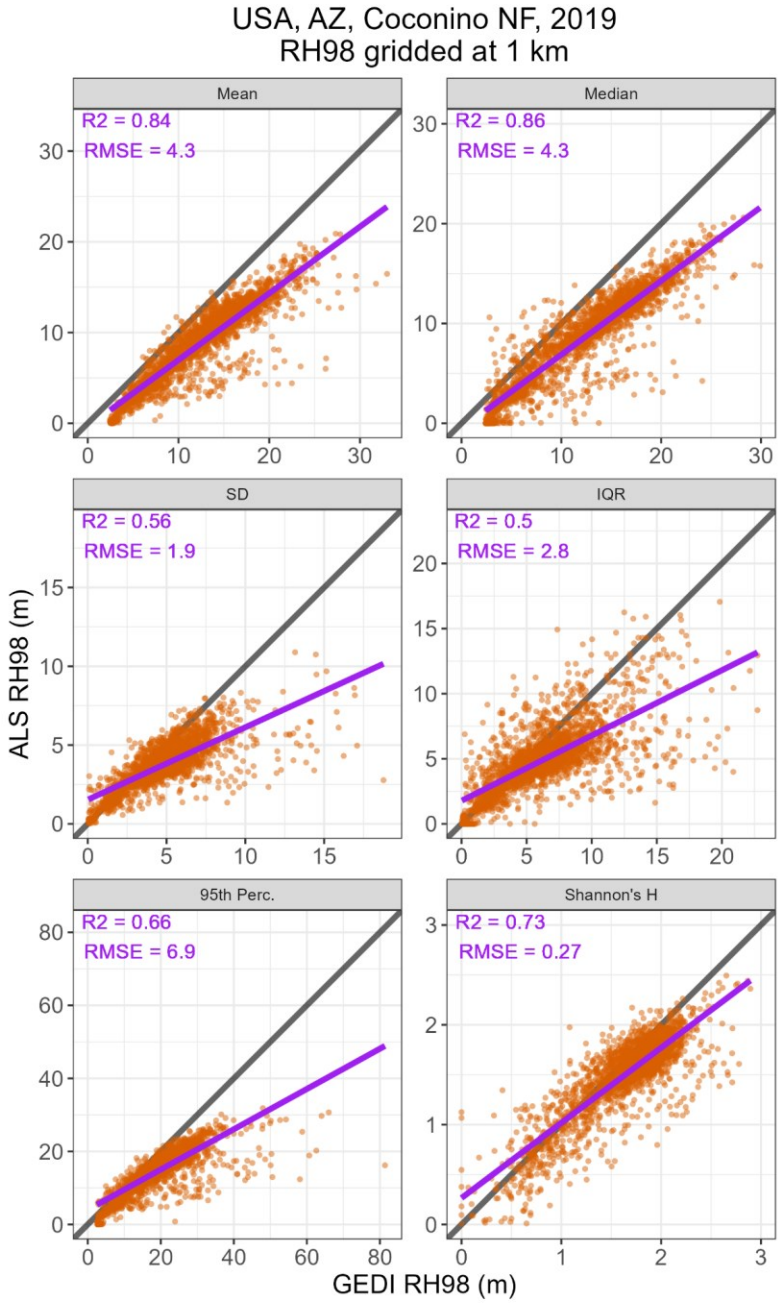

Figure 3. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

Table 5. Summary statistics for Coconino National Forest 1 km validation.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples

RH98	Mean	4.3	49.0	3.7	0.84	2408
RH98	Median	4.3	51.6	3.8	0.86	2408
RH98	SD	1.9	49.2	1.3	0.56	2408
RH98	IQR	2.8	57.7	1.9	0.50	2408
RH98	95th Perc.	6.9	45.5	5.2	0.66	2408
RH98	Shannon’s H	0.3	18.0	0.2	0.73	2408

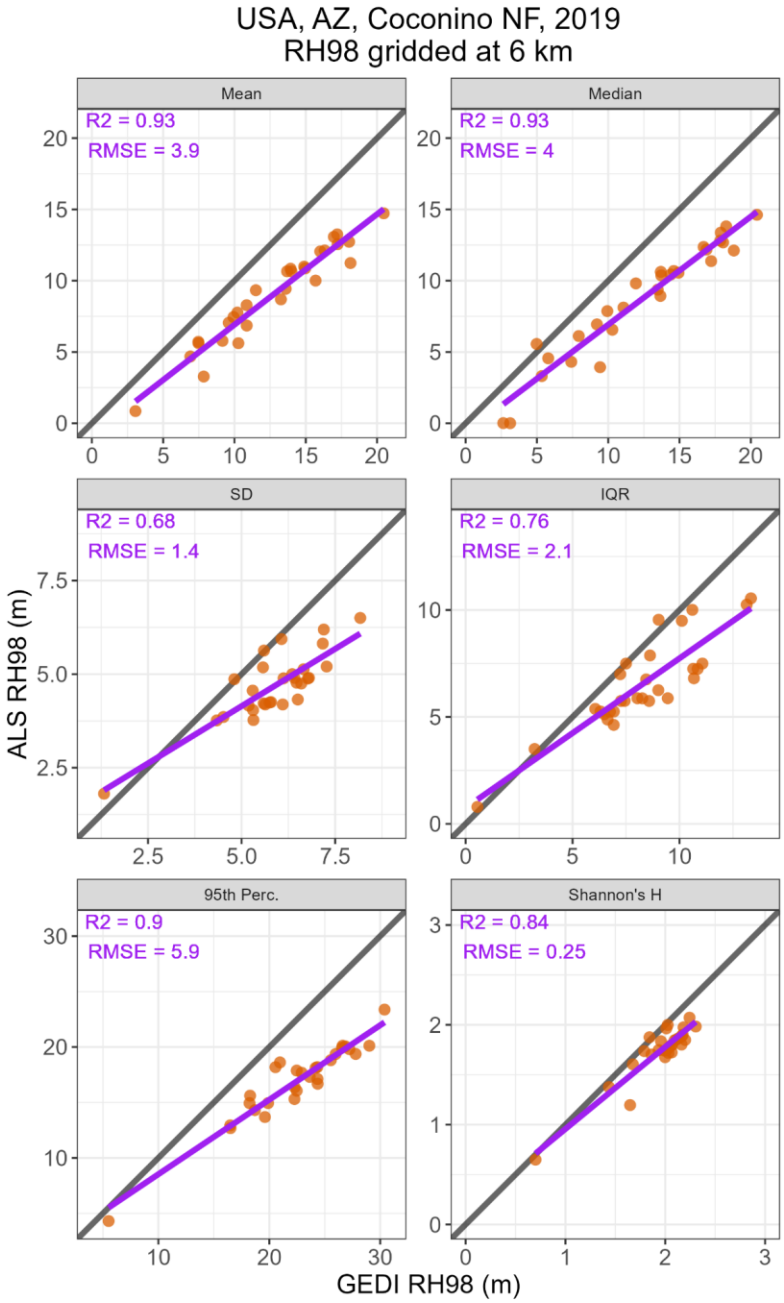

Figure 4. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 6 km cells.

Table 6. Summary statistics for Coconino National Forest 6 km validation.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples

RH98	Mean	3.9	43.3	3.7	0.93	29
RH98	Median	4.0	45.6	3.7	0.93	29
RH98	SD	1.4	29.4	1.2	0.68	29
RH98	IQR	2.1	33.0	1.8	0.76	29
RH98	95th Perc.	5.9	34.8	5.6	0.90	29
RH98	Shannon’s H	0.2	14.0	0.2	0.84	29

a. NASA CMS Indonesia

ALS data were acquired for select regions of Kalimantan, Indonesia in 2014. We used a 3 m spatial resolution canopy height model for validation. Given the relatively small swath width and collection extents of this campaign we only performed validation at 1 km spatial resolution. Note that there is at least 5 years between ALS and GEDI lidar acquisition, so some error may be attributable to growth and/or non-stand-replacing disturbances.

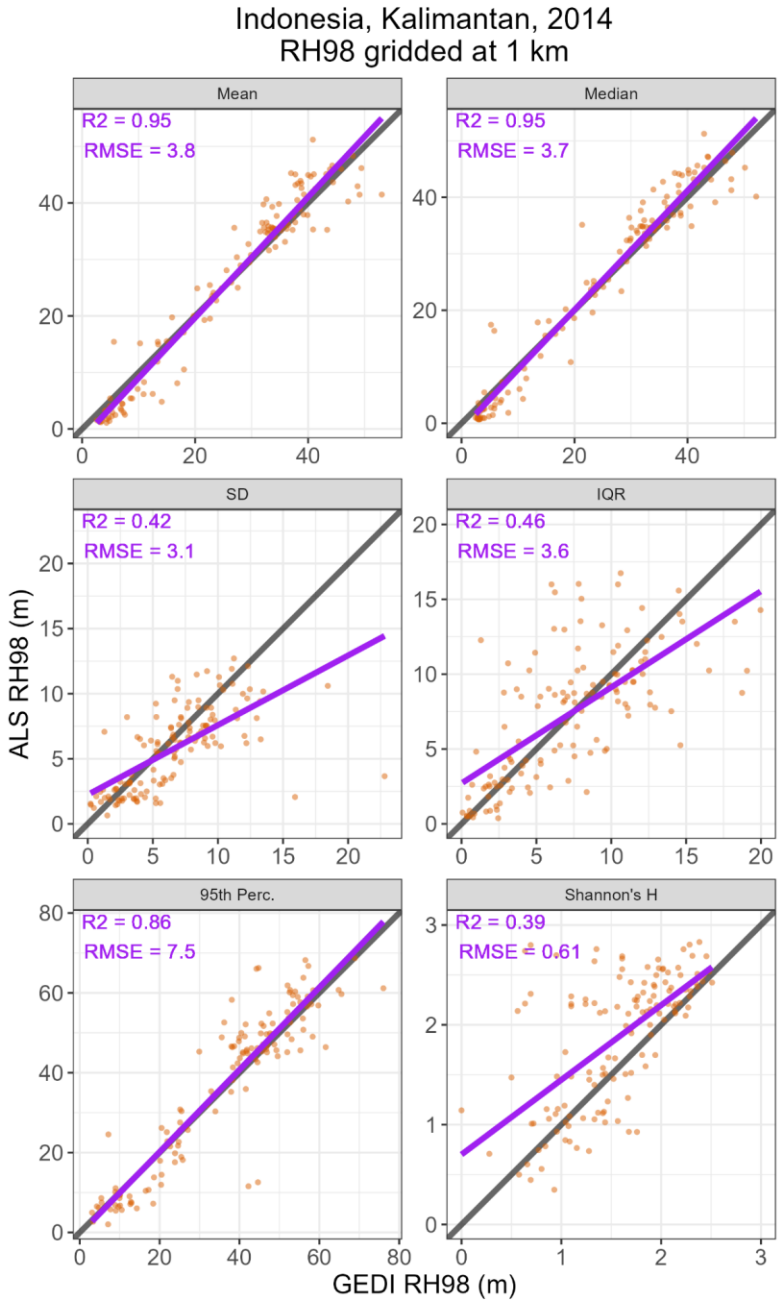

Figure 5. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

Table 7. Summary statistics for NASA CMS Indonesia 1 km validation.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples

RH98	Mean	3.8	14.7	2.9	0.95	135
RH98	Median	3.7	14.7	2.7	0.95	135
RH98	SD	3.1	52.6	2.0	0.42	135
RH98	IQR	3.6	48.2	2.6	0.46	135
RH98	95th Perc.	7.5	21.1	5.2	0.86	135
RH98	Shannon's H	0.6	32.6	0.4	0.39	135

b. EFForTS Indonesia

ALS data were acquired for select regions of Jambi, Indonesia in 2020 and 2022. We mosaiced the 1 m canopy height models from the two years, giving priority to the data from 2020 since it covered more area. Rasters of additional ALS metrics (ZQ50, LAI, and FHD) were also available at 10 m spatial resolution. These additional ALS metrics were computed using slightly different equations but are still useful for preliminary validation of gridded GEDI RH50, PAI, and FHD. Given the relatively small collection extent of this campaign we only performed validation at 1 km spatial resolution.

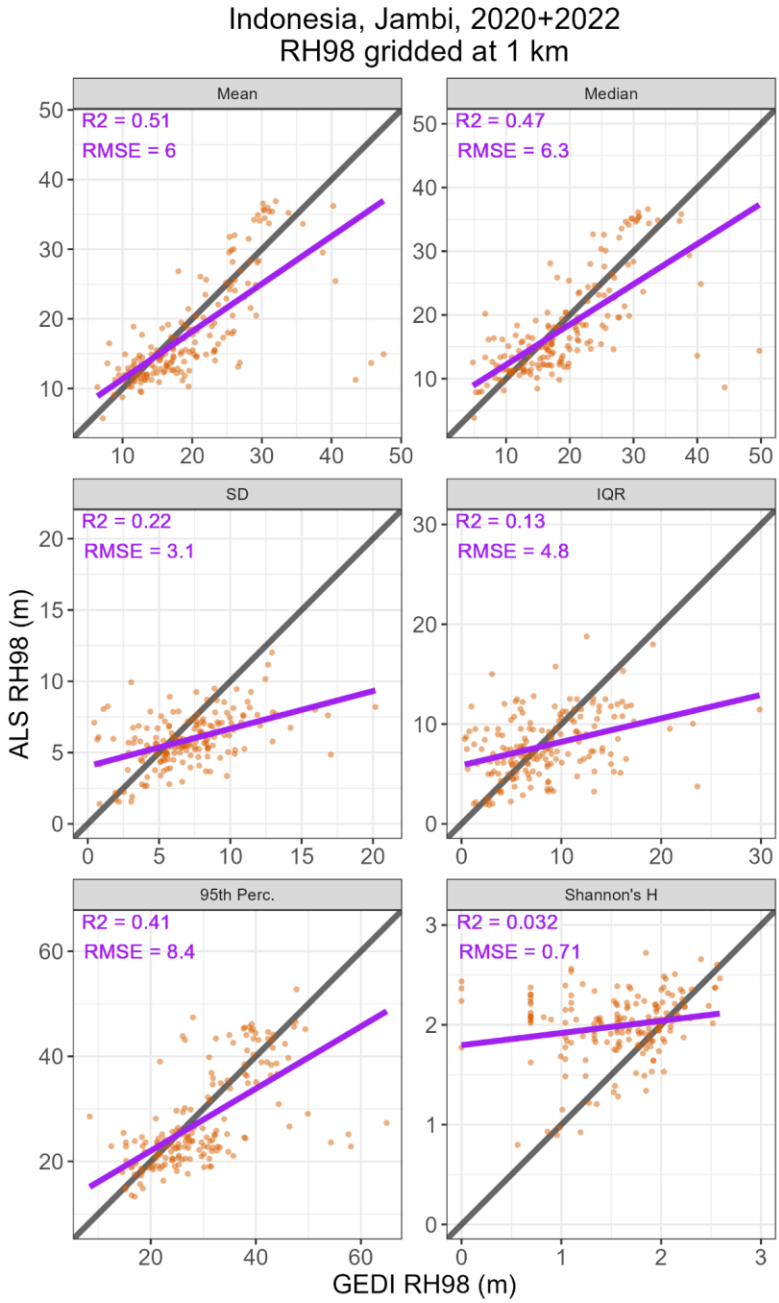

Figure 6. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

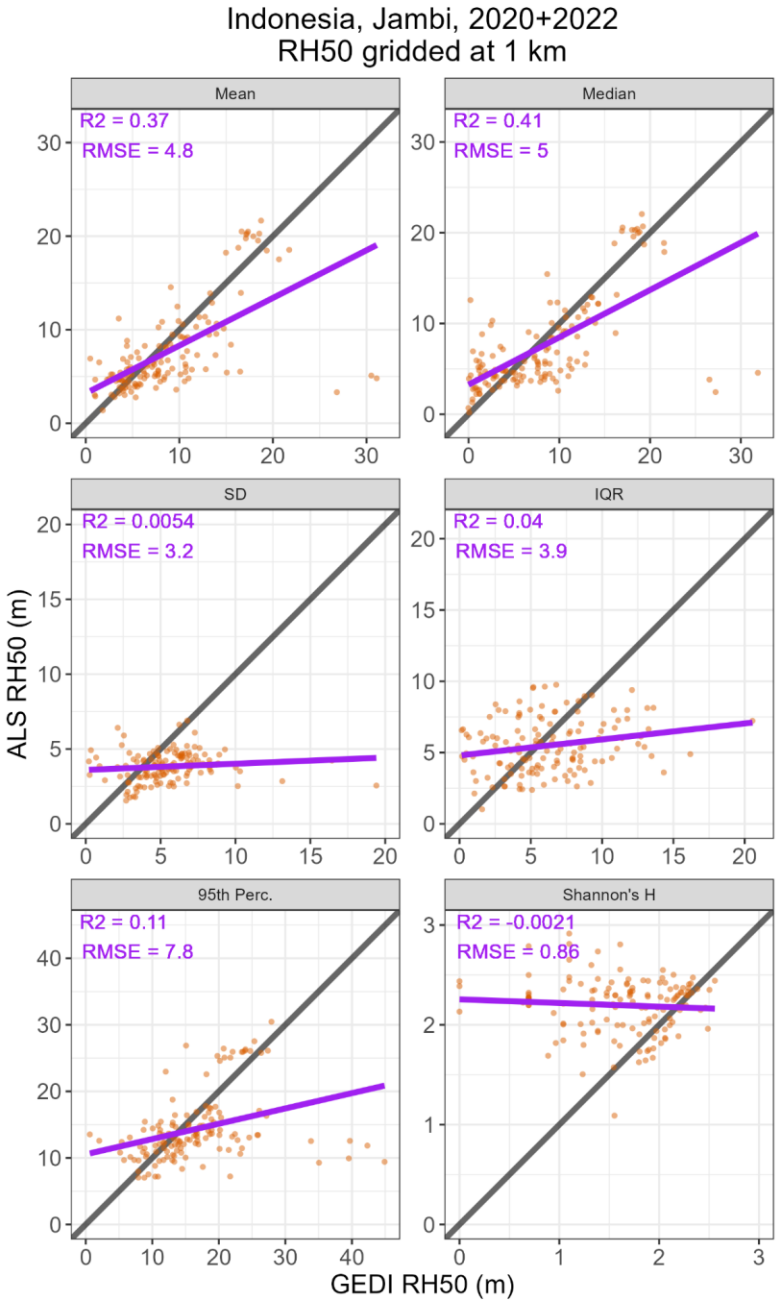

Figure 7. Comparison of ALS RH50 (ZQ50) and GEDI RH50 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

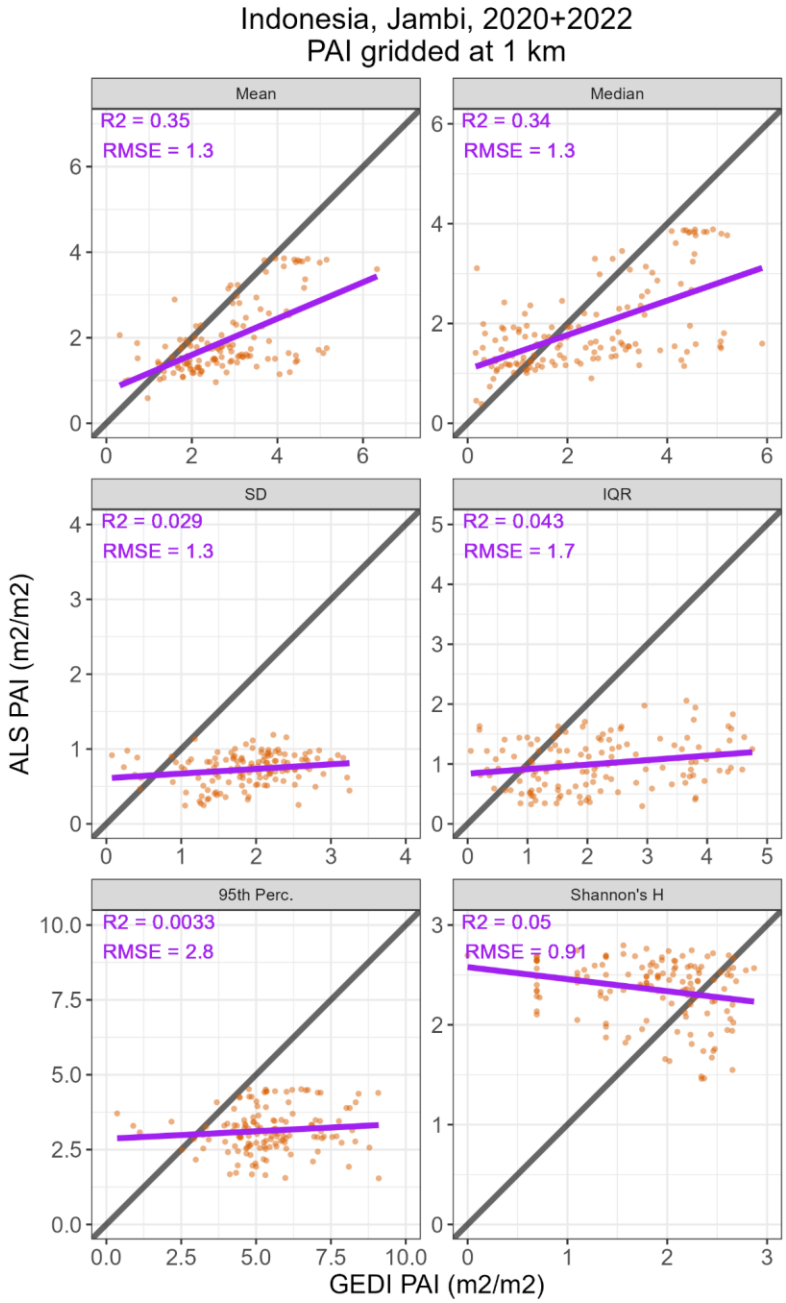

Figure 8. Comparison of ALS PAI (LAI) and GEDI PAI using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

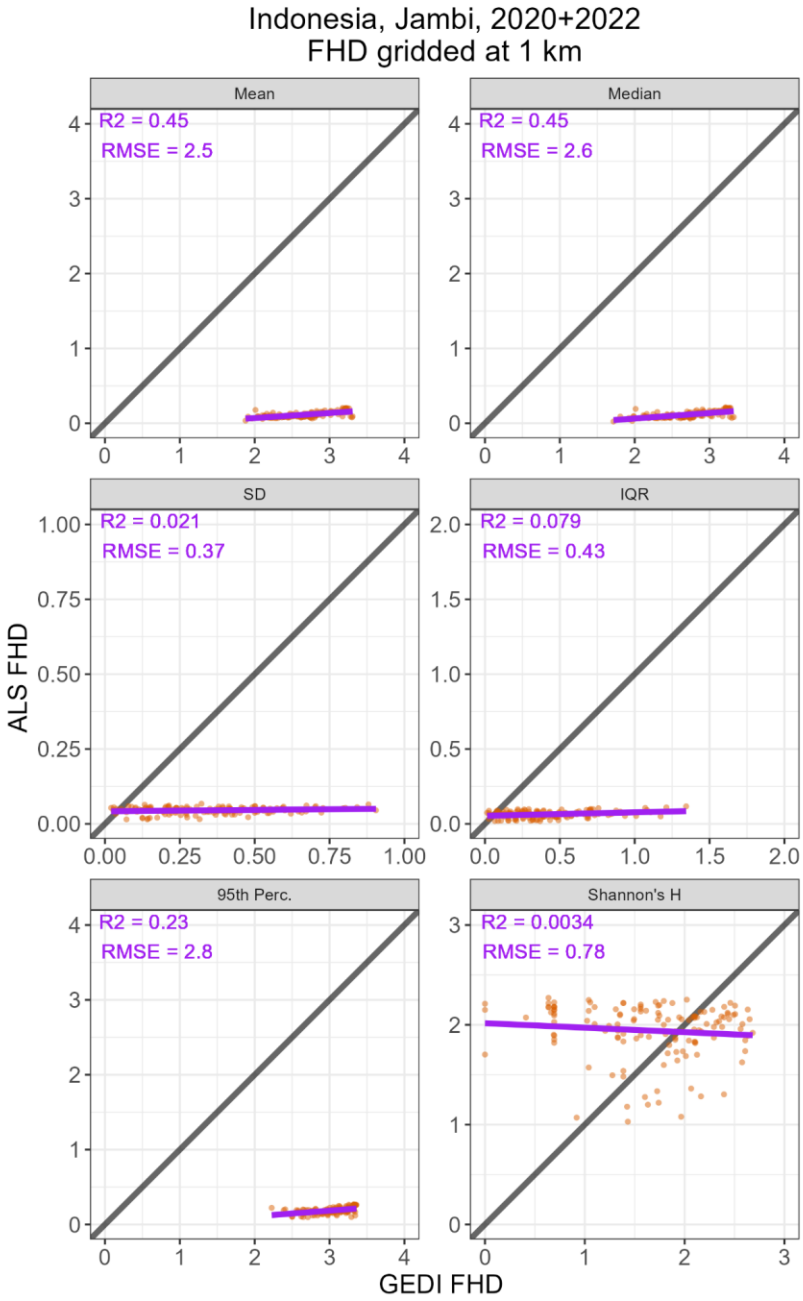

Figure 9. Comparison of ALS FHD and GEDI FHD using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

Table 8. Summary statistics for EFForTS Indonesia 1 km validation.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples

RH98	Mean	6.0	33.4	3.9	0.51	176
RH98	Median	6.3	35.2	4.2	0.47	176
RH98	SD	3.1	52.4	2.3	0.22	176
RH98	IQR	4.8	61.4	3.5	0.13	176
RH98	95th Perc.	8.4	30.3	5.8	0.41	176
RH98	Shannon’s H	0.7	35.7	0.5	0.03	176
RH50	Mean	4.8	61.8	2.8	0.37	138
RH50	Median	5.0	66.8	3.2	0.41	137
RH50	SD	3.2	82.5	2.3	0.01	138
RH50	IQR	3.9	70.1	3.1	0.04	138
RH50	95th Perc.	7.8	54.4	5.0	0.11	138
RH50	Shannon’s H	0.9	38.9	0.6	0.00	138
PAI	Mean	1.3	64.8	1.0	0.35	138
PAI	Median	1.3	68.7	1.0	0.34	138
PAI	SD	1.3	180.7	1.2	0.03	138
PAI	IQR	1.7	165.4	1.3	0.04	138
PAI	95th Perc.	2.8	89.5	2.4	0.00	138
PAI	Shannon’s H	0.9	38.5	0.7	0.05	138
FHD	Mean	2.5	2258.2	2.5	0.45	138
FHD	Median	2.6	2295.3	2.5	0.45	138
FHD	SD	0.4	810.7	0.3	0.02	138
FHD	IQR	0.4	685.4	0.3	0.08	138
FHD	95th Perc.	2.8	1530.1	2.8	0.23	138
FHD	Shannon’s H	0.8	39.9	0.6	0.00	138

c. SAFE Malaysia

ALS data were acquired for the SAFE project landscape, Maliau Conservation Area and Danum Valley of Sabah, Malaysia in 2014. We used a 1m spatial resolution canopy height model for validation. We also used 20 m gridded maps of total PAI and FHD for validation. These additional ALS metrics were computed using slightly different equations but are still useful for preliminary validation of gridded GEDI PAI and FHD. Given the relatively small collection extents of this campaign we only performed validation at 1 km spatial resolution. Note that there is at least 5 years between ALS and GEDI lidar acquisition, so some error may be attributable to growth and/or non-stand-replacing disturbances.

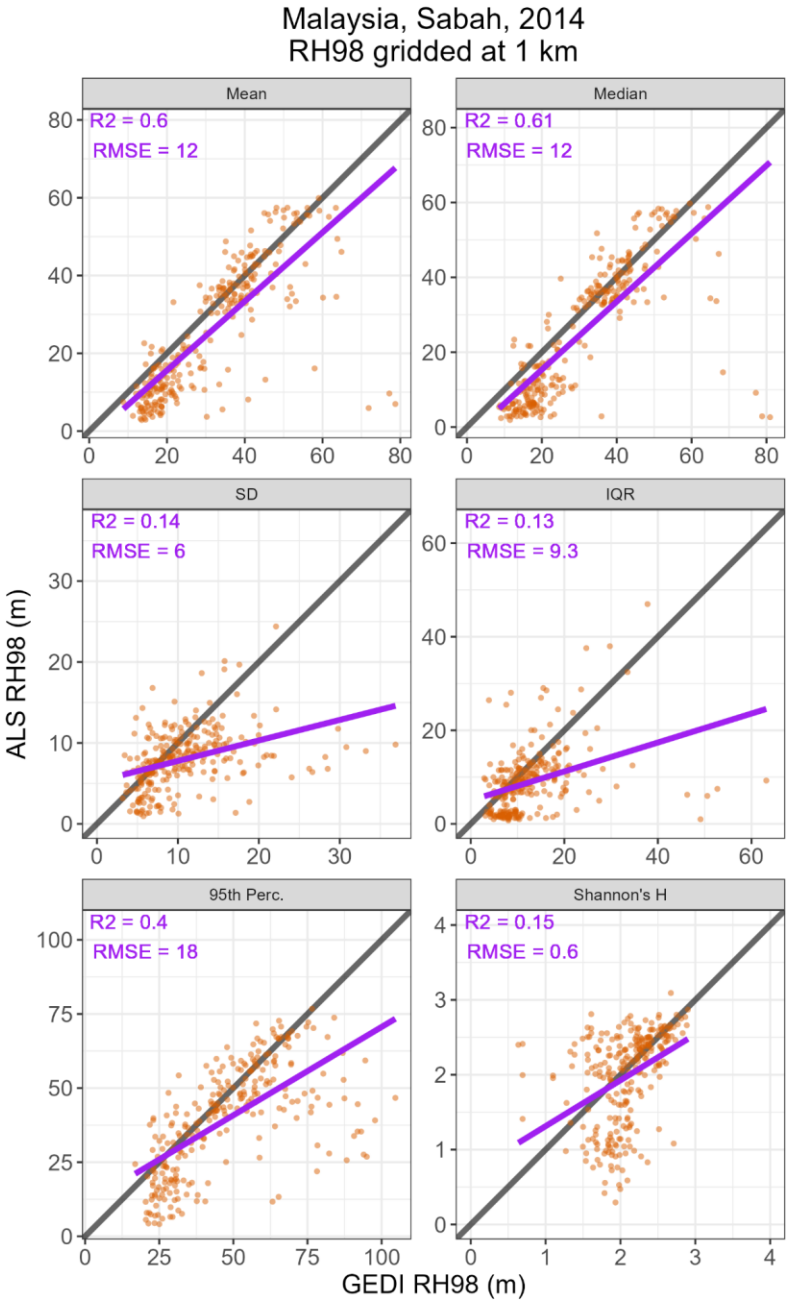

Figure 10. Comparison of ALS RH98 and GEDI RH98 using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

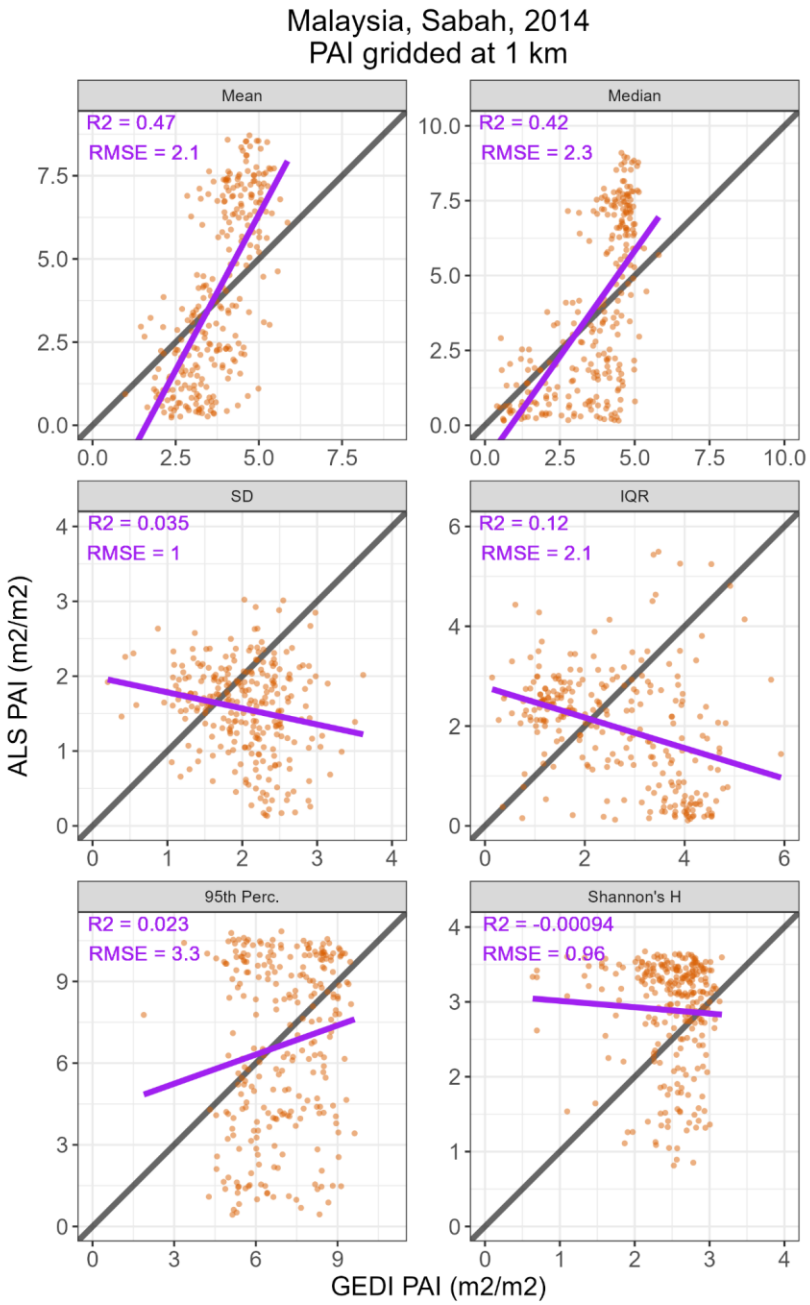

Figure 11. Comparison of ALS PAI and GEDI PAI using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

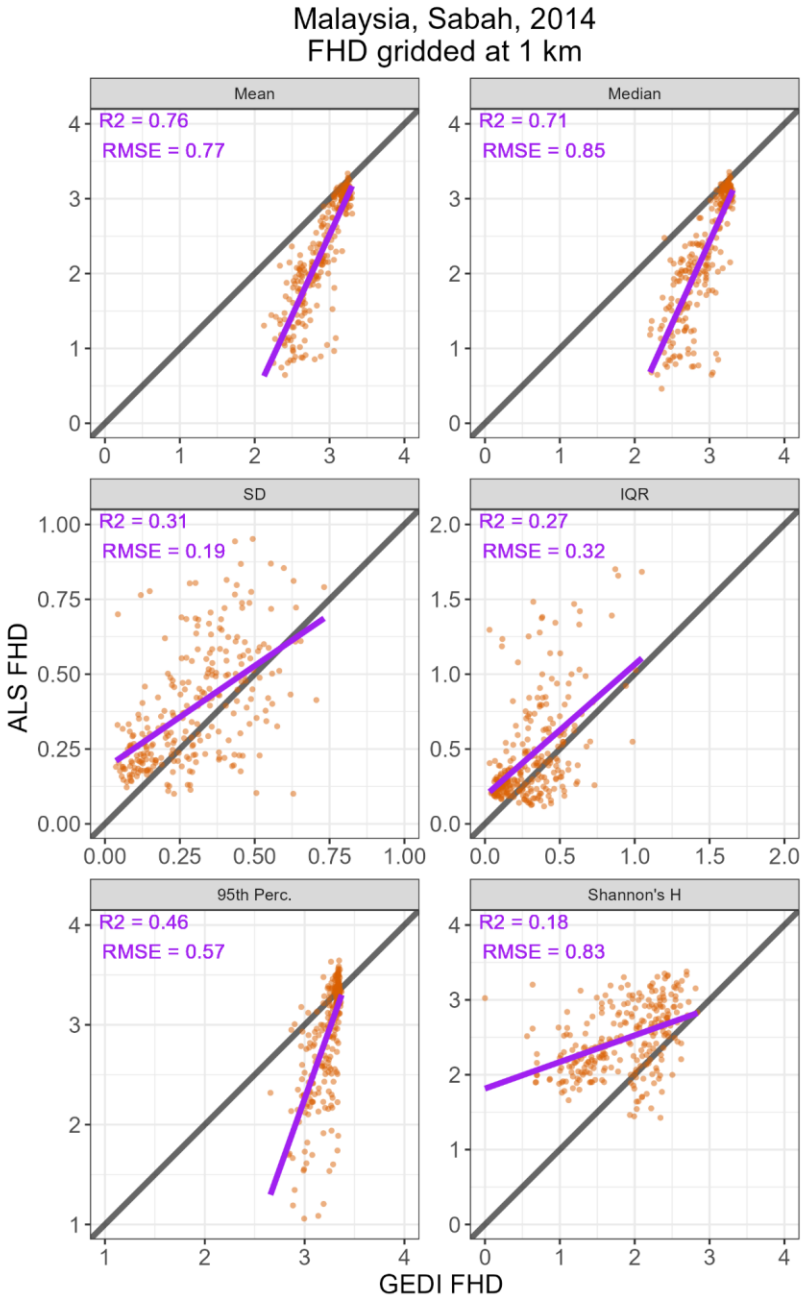

Figure 12. Comparison of ALS FHDand GEDI FHD using mean, median, standard deviation (SD), interquartile range, 95th percentile, and Shannon's H aggregation methods. The black line has a 1:1 relationship while the purple line corresponds to a linear fit (ALS ~ GEDI) of 1 km cells.

Table 9. Summary statistics for SAFE Malaysia 1 km validation of RH98, PAI, and FHD.

GEDI metric	Aggregation Statistic	RMSE (m)	Rel. RMSE (%)	MAE (m)	Adj. R^2	N 1 km^2 samples

RH98	Mean	11.7	45.9	7.7	0.60	266
RH98	Median	12.3	50.1	8.0	0.61	266
RH98	SD	6.0	75.2	4.0	0.14	266
RH98	IQR	9.3	104.2	6.0	0.13	266
RH98	95th Perc.	18.0	45.6	12.1	0.40	266
RH98	Shannon's H	0.6	30.5	0.5	0.15	266
PAI	Mean	2.1	53.3	1.8	0.47	269
PAI	Median	2.3	59.0	1.9	0.42	269
PAI	SD	1.0	65.3	0.8	0.03	269
PAI	IQR	2.1	106.1	1.7	0.12	269
PAI	95th Perc.	3.3	48.9	2.7	0.02	269
PAI	Shannon's H	1.0	33.3	0.8	0.00	269
FHD	Mean	0.8	33.5	0.6	0.76	269
FHD	Median	0.8	36.6	0.6	0.71	269
FHD	SD	0.2	50.3	0.2	0.31	269
FHD	IQR	0.3	69.2	0.2	0.27	269
FHD	95th Perc.	0.6	19.7	0.4	0.46	269
FHD	Shannon's H	0.8	33.7	0.7	0.18	269

3. References

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