A Validation of Coarse Scale Global Vegetation Height Map for Biomass Estimation in Hemiboreal Forests in Estonia

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Abstract

A public release of global vegetation height map, based on data from spaceborne lidar GLAS, was validated using forest management inventory (FI) data and airborne laser (ALS) data from two 15 × 15 km test sites in Estonia: the first one in Aegviidu and the second one in Laeva. For each global vegetation height (GVH) map pixel located in the test sites we calculated forest height based on the FI data and on ALS data. Linear regression analysis was then used to evaluate the relationships between GVH map values (H_{GVH}), FI forest height (H_{FI}) and ALS-based Lorey's forest height (H_{ALS}). In the second test H_{GVH} and H_{ALS} were evaluated for estimating forest biomass using regression analysis. The biomass was calculated for each GVH pixel using FI data and allometric regression models.

The correlation between H_{GVH} and H_{FI} or H_{ALS} in both test sites was weak – in Aegviidu $r < 0.25$ and in Laeva $r < 0.15$; and, the relationship was not statistically significant in Laeva. The airborne lidar based H_{ALS} had a strong positive correlation with forest biomass and the determination coefficient of linear regression was $R^2 > 0.6$ ($p < 0.01$) in both test sites. The relationship between H_{GVH} and biomass was scattered and determination coefficient for linear model was small ($R^2 < 0.15$, $p < 0.01$).

Although in this study only weak correlation between measured forest heights (H_{FI} and H_{ALS}) and spaceborne lidar based HGVH was found, the GVH type estimates are essential for the areas, where forest inventory data or airborne lidar data is not available. The obtained results show that forest height estimates from ALS or spaceborne lidar could be used directly for estimating biomass in managed hemiboreal forests at coarse spatial resolution.

Keywords: hemiboreal forests, airborne laser data, forest inventory data, global vegetation height map, forest biomass.

Introduction

Airborne laser scanning (ALS) has been a success story in operational forest inventories in many countries. The ALS data based forest structure variables (Næsset 1997, Korhonen et al. 2011, Lang et al. 2012) can further be used for monitoring carbon balance and biomass stocks (Patenaude et al. 2004, Popescu and Zhao 2008, Popescu et al. 2011, Zhang et al. 2014). In addition to the regional laser scanning from airplanes or drones, spaceborne laser scanning has also gained importance for global scale applications (Lefsky 2010). The Geoscience Laser Altimeter System (GLAS) aboard Ice, Cloud, and Land Elevation Satellite (ICESat, Schutz et al. 2005) has been used to construct global wall-to-wall maps of biomass and carbon (Hese et al. 2005, Boudreau et al. 2008, Yu et al. 2015, Lefsky et al. 2005, Zhang et al. 2014), to estimate vegetation height (Gwenzi and Lefsky 2014, Miller et al. 2011, Lefsky 2010, Simard et al. 2011), for monitoring and mapping forest disturbances (Dolan et al. 2011, Hayashi et al. 2015) and for digital elevation maps (Duncanson et al. 2010, Chen 2010). The spaceborne products cover wider areas with smaller time-lapse providing a fast overview at coarser spatial resolution compared to airborne laser data. However, before these global products can be used for local estimation of biomass or other variables, a careful validation should be conducted.

The height of a forest or a tree is the basic variable in forest description and modelling. Forest height is also the most important parameter for estimating volumes, biomass, carbon stocks etc. The most commonly used tree height definition is the vertical distance from the root collar of the tree to the highest branch or top (Van Laar and Akça 2010). While the height definition seems to be clear, the determination of root collar position is already a source of error - for example in drained forests in former

swamps, where the soil surface sinks due to the organic matter decay after draining (Jürimäe 1966).

Average height of several trees growing on an area can be calculated in different ways. For a rather homogeneous part of a forest (forest stand), the height may be calculated as an average of single measured tree heights. More commonly Lorey's height is used, which is stem basal area weighted average height. The average height of multiple forest stands, as found within a larger area corresponding for example to a global scale map pixel, is not a usual variable in forest inventories. The area of the global vegetation height (GVH) map (Simard et al. 2011) pixel used in this study is about 50 hectares in Estonia coordinate system. The average forest stand size in our test sites is about 2 hectares, and the 50 hectare pixels are internally heterogeneous with forests up to 30 metres in height mixed with crop fields and other land use types at the edges of forest patches. Depending on where the GLAS pulse hits the pixel, the estimated height might not reflect the average forest height at all.

Forest height and biomass are known to be well correlated (Marklund 1987, Repola 2009, Zianis et al. 2005) and biomass monitoring is another common by-product of global vegetation height maps especially for areas with no ALS data cover or forest inventory (FI) data. Forest biomass is also the key variable for estimating carbon stocks (Latifi et al. 2015, Main-Knorn et al. 2013); therefore, the validation of global vegetation height map products is important before making any further analyses.

The goal of this study was to validate the freely available global vegetation height map (GVH) published by Simard et al. (2011), in our two Estonian test sites with diverse multi-layer and mixed hemiboreal forests. Biomass estimates were calculated using the forest management inventory (FI) database and Repola (2008, 2009) biomass models. Biomass was then calculated for each GVH map pixel found in our test sites. Then the forest height from the GVH map (H_{GVH}) and ALS based forest height (H_{ALS}) were tested as biomass predictor variables using regression analysis.

Material and Methods

Test sites and forest inventory data

The first validation site (15×15 km) is located near Aegviidu (centre coordinates in EPSG:3301 projection: 6572701 N; 587333 E), in North Estonia (Figure 1) and was established by Anniste and Viilup (2011) for ALS data based forest inventory study. The second 15×15 km test site is located near Laeva (centre coordinates in EPSG:3301 projection: 6490854 N; 642472 E), in the south-eastern part of Estonia (Figure 1) and was established in 2013. The test site is described in more detail by Lang et al. (2014).

Aegviidu test site is dominated by coniferous forests with the main species being Scots pine (*Pinus sylvestris* L.). Laeva test site is dominated by deciduous forests where the most widespread species are silver birch (*Betula pendula* Roth) and trembling aspen (*Populus tremula* L.). These two contrasting test sites represent typical hemiboreal managed forests.

The FI database contained data for 14,263 stands in Aegviidu test site and data for 8950 stands in Laeva. The forest stands in Aegviidu test site were inventoried during 2007-2010, the data for Laeva test site was collected mostly in 2013 during regular forest management inventory. The forest height in FI is defined as the average height of trees with the square mean diameter. To match the GLAS data collection time period used by Simard et al. (2011) the FI data was predicted to the year 2005 using algebraic difference model published by Kangur et al. (2007).

The biomass for each GVH pixel was calculated using Repola (2008, 2009) models based on data from the FI database. Next, the FI stand map was split and sampled according to the GVH pixel shape files (Figure 1). For each GVH pixel forest inventory data based height (H_{FI}) and biomass were then calculated as the stand polygon area weighted mean values.

Global vegetation height map

The spaceborne lidar based GVH map published by Simard et al. (2011) is constructed using GLAS data from ICESat mission. They used a raster based approach to construct the GVH map: the global map was first divided into 1×1 km pixels, which then were classified as forest and non-forest using the Global Land Cover Map (GlobCover, Hagolle et al. 2005). The GLAS transmits laser pulses (1064 nm), which have a footprint of about 60 m in diameter on ground and records the reflected signal waveform (Schutz et al. 2005), so each pulse covers less than one percent of the GVH map pixel area in Estonia. The data used for the map was collected in 2005 from May 20th to June 26th. This is the period just after the active bud burst and time of rapid increase of foliage mass and the time of leaf properties change in Estonia. Therefore for the validation we used two ALS datasets, one from leaf-off and second from leaf-on conditions as the leaf properties and canopy transmittance vary substantially between spring and summer time, especially in deciduous forests (Brandtberg 2007). For calculating the forest canopy height (H_{GVH}) Simard et al. (2011) used the GLAS level-2 altimetry GLA14 product version 31, which is designed for land surface elevation assessment. The GLA14 product defines the pulse return signal start as the location, at which the signal is 3.5 times the noise standard deviation. Ground is defined as the last Gaussian peak of the signal. The relative height RH100 is then defined as

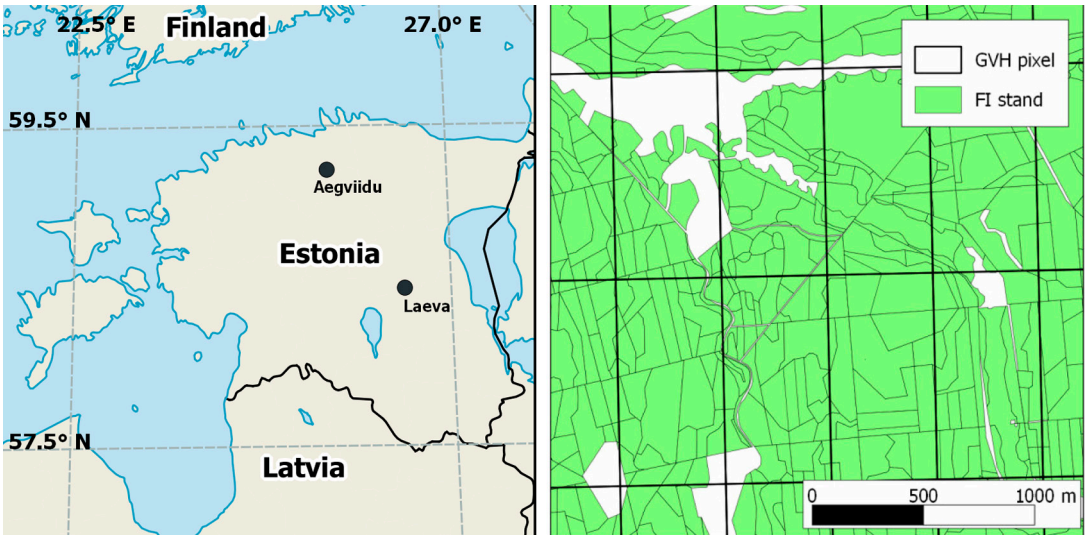

Figure 1. Aegviidu and Laeva test sites (left). An example of the Global Vegetation Height (GVH) pixel borders over the forest inventory (FI) stand map in Aegviidu test site (right)

the distance between these two signal peaks and is then used for modelling the top canopy for GVH map (H_{GVH}).

Simard et al. (2011) used validation data from 66 globally distributed FLUXNET sites, which have measured canopy height data available and showed the linear relationship with $R^2 = 0.49$ (with outliers excluded $R^2 = 0.69$). Due to sparse or missing GLAS data in some regions, Moderate Resolution Imaging Spectroradiometer (MODIS) data, elevation data from the Shuttle Radar Topography mission and climatology map data etc., were used to estimate vegetation height in for the pixels.

We extracted the pixel boundaries of the GVH raster map as a new map of vector polygons, which was then resampled into Estonian basic map coordinate system (EPSG:3301). This approach decreases substantially the errors related to georeferencing of the large pixels for spatial queries from detailed maps. The size of each GVH polygon was after the coordinate system transformation about 500 by 1000 metres (Figure 1). The polygons were used as the elementary observation units and are further in the text referred as GVH pixels.

The list of the GVH pixels was filtered to select those which had forest land over 75 percent and clear cut area during 1996…2013 less than 50 percent. The stand replacing disturbance map was obtained from Urmas Peterson (Tartu Observatory, personal contacts) and the map construction methods are described by Peterson et al. (2004). The total count of GVH pixels left after the filtering in Aegviidu test site was 226 and in Laeva test site we had 69 GVH pixels.

Airborne lidar data

The leaf-on ALS data for Aegviidu was collected in 2008 summer from July to beginning of September and leaf-off ALS data set was collected in May 2009. In Laeva test site, both leaf-off and leaf-on datasets were collected in 2013: leaf-off dataset in May and leaf-on dataset in July. All ALS data was collected by Estonian Land Board using the Leica ALS50-II scanner on board a Cessna Grand Caravan 208B airplane. This Leica scanner operates on the same 1,064 nm wavelength as does the GLAS. In Aegviidu test site the average point density in the ALS data was 0.45 points m^{-2}. In Laeva test site the point density was approximately 2 points m^{-2}. The ALS data was processed using FUSION/LDV freeware (McGaughey 2014) modules GroundFilter, GridSurfaceCreate, PolyClipData and CloudMetrics. ALS data based digital terrain model with a 5 metres pixel was created with GroundFilter and GridSurfaceCreate and was then used to calculate pulse return height relative to the ground. The ALS point clouds were extracted using the GVH pixel polygon shapefiles and the FI stand polygons with PolyClipData module. Based on previous research in Aegviidu test site (Lang et al. 2012), different height statistics were calculated with CloudMetrics and 80-percentile was chosen to estimate H_{ALS} with linear model 1. Reflections below two metres were excluded from the percentile calculations to reduce the influence of near ground vegetation.

$$H_{ALS} = a_i \times P_{80} + b_i, \qquad (1)$$

where

H_{ALS} is the ALS-based forest height (m) for the GVH pixel,

P_{80} is 80-percentile of the ALS point cloud,

a_i, b_i are estimated parameters depending on test site and leaf-on/leaf-off flights. Values for a_i and b_i are given in Table 1.

Table 1. Model (1) parameter values and model statistics for test sites and different phenology stages

Test site	ALS flight time	Model (1) parameters and statistics				
		a_i	b_i	R^2	RSE (m)	*p*-value
Laeva	Leaf-off	1.27	- 3.65	0.93	1.83	< 0.01
	Leaf-on	1.21	- 4.01	0.96	1.32	< 0.01
Aegviidu	Leaf-off	0.94	3.63	0.96	0.83	< 0.01
	Leaf-on	0.94	3.48	0.94	1.04	< 0.01

The site and phenology specific models (Eq.(1), Table 1) for H_{ALS} were created using measurements from 46 forest stands in Aegviidu (Arumäe and Lang 2013) and using data from 94 permanent forest growth study sample plots (Kiviste et al. 2015) in Laeva test site. The plots in Laeva were measured in 2010 and 2011 and in Aegviidu measurements were done in 2011. The parameters for the regression model (1) were estimated using R (R Core Team 2014) lm procedure.

Using the same lm procedure we compared all the derived forest heights (H_{FI}, H_{ALS} and H_{GVH}). Bias estimates for these regression analyses were calculated as $\sum(Y - X) / N$, where N is the number of observations, X is the independent variable and Y is the dependent variable.

Results

Forest height

We found only a weak correlation ($r < 0.25$, $p < 0.01$) between H_{GVH} calculated by Simard et al. (2011) and H_{ALS} in both test sites (Figure 2A and 2D). In Laeva the correlation between H_{GVH} and H_{ALS} was not statistically significant ($p > 0.05$). Similar weak correlations ($r < 0.2$) were found for H_{GVH} and H_{FI} in Aegviidu and Laeva as seen in Figure 2B and 2E. The relationship was significant in Aegviidu ($p < 0.01$), but in Laeva the relationship was not statistically significant ($p > 0.05$). Figure 2 shows the lack of variation in H_{GVH} compared to H_{ALS} and H_{FI} and a large error in estimating heights below 15 metres. On the other hand, as found in many previous studies, there was a strong correlation between H_{ALS} and H_{FI} using linear model in both test sites (Figure 2C and 2F) with coefficient of correlation over 0.6 ($p < 0.01$).

The bias on Figure 2F is caused partially by the time difference between FI height data (predicted to year 2005) and ALS data acquisition (2013). *T*-test confirmed that bias in all cases was statistically significant ($p < 0.01$). The large bias may also be caused by using the same 80-percentile (P_{80}) height method for estimating canopy height for a large 50 hectare pixel and a small 10-15 metre radius plot. To estimate the model (1) small sample plots were used as is the usual approach in forest inventory. The model was then applied to the GVH pixel-based point clouds. The explanation for the extracted point cloud size influence to the H_{ALS} follows from the definition of P_{80}: this is the height in ALS point cloud from which 80 % of points are located lower. While P_{80} is usually well correlated with canopy top height we do not know, how high the rest 20 % of points are located. In point clouds extracted for 50 hectare GVH pixels containing different forest stands, the P_{80} is determined by the highest stands (or groups of trees) covering roughly 20 % of the area. For comparison, in Laeva test site we calculated P_{80} of ALS point height distribution for GVH pixels from a 20 m resolution raster map of P_{80} instead of 50 ha large original point clouds. The average forest height in Laeva test site was then 2.8 metres lower when calculated with the model (1) and using P_{80} averaged from the 20 m raster map for each GVH pixel.

There was no substantial difference in relationship between H_{GVH} and H_{ALS} in leaf-off and leaf-on ALS data in Aegviidu test site, where evergreen coniferous forests are dominating (Table 2). In Laeva test site, where deciduous broadleaf forests are in majority, the linear correlation between H_{GVH} and H_{ALS} was not significant (Table 2).

The H_{GVH} relationship to H_{ALS} or H_{FI} at GVH pixel level was absent or weak (Figure 2A, 2D). To verify if H_{GVH} estimates are reasonable, when the GVH pixel values are averaged over a larger area we compared the mean H_{GVH}, H_{FI} and H_{ALS} on test site basis. The results (Table 3) showed no significant differences for leaf-on and leaf-off ALS datasets in Aegviidu and mean H_{ALS} for both spring and summer datasets were about 1.8 metres lower than H_{GVH}. To compare the significance of differences of test site mean forest height estimations *t*-test was used. In Laeva the difference between leaf-off and leaf-on ALS height estimates was significant (Table 3). Based on leaf-off ALS dataset, the mean H_{ALS} was 3.0 metres lower than using leaf-on ALS dataset. This decrease in test site mean height is probably related to the ALS pulse being split more per pulse in leaf-off conditions compared to leaf-on conditions in deciduous forests. In Laeva, the share of first returns from total number of returns was 85.5 % in leaf-on conditions and 76.5 % in leaf-off condition. In Aegviidu, where evergreen coniferous forests dominate, the corresponding shares were 75 % and 71.8 %. The overall mean of H_{GVH} and H_{ALS} in leaf-on ALS datasets was not significantly different in Laeva. H_{ALS} was calculated using the large 50-hectare point clouds and possible influence of the ALS point cloud sample was discussed earlier in the text.

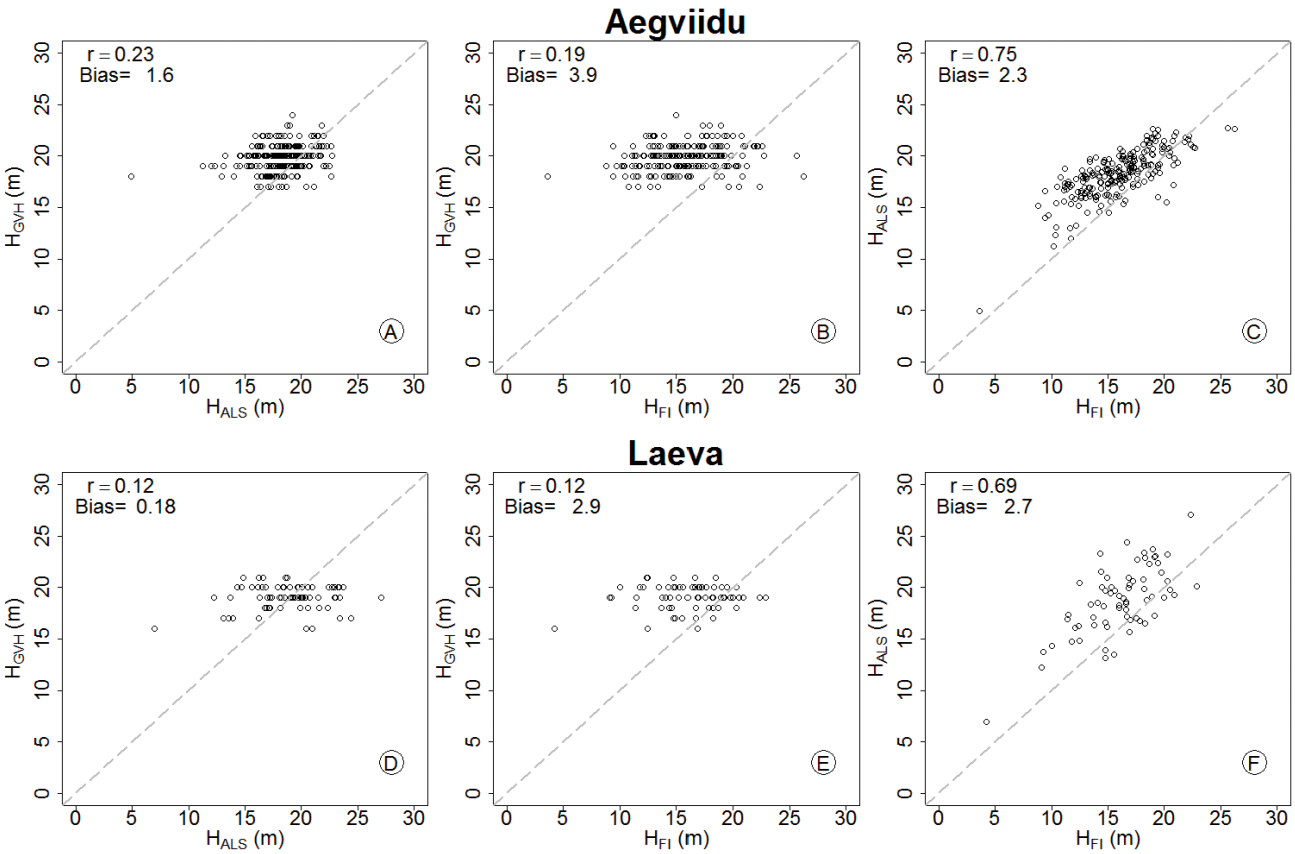

Figure 2. Correlation between forest height estimates using GVH map pixels as observations. Leaf-on ALS data is used for the Figures

Table 2. The relationship between H_{GVH} and H_{ALS} described by linear regression model ($H_{GVH} = aH_{ALS} + b$)

Test site	ALS flight time	H_{GVH} and H_{ALS} linear regression model parameters				
		b	a	RSE	R^2	*p*-value
Laeva	Leaf-off	19.58	*- 0.04*	1.22	0.00	> 0.45
	Leaf-on	18.19	*0.04*	1.22	0.00	> 0.32
Aegviidu	Leaf-off	16.98	0.16	1.27	0.08	< 0.01
	Leaf-on	17.42	0.13	1.29	0.05	< 0.01

Table 3. Overall average of H_{GVH} compared to H_{ALS} and H_{FI} averages in Aegviidu and Laeva test sites. Standard error is given in brackets

Test site	ALS flight time	Forest height estimate		
		H_{ALS} (m)	H_{GVH} (m)	H_{FI} (m)
Aegviidu	Leaf-off	18.0 (0.15)	19.8 (0.10)	15.9 (0.21)
	Leaf-on	18.2 (0.15)		
Laeva	Leaf-off	15.8 (0.38)	19.0 (0.15)	16.1 (0.40)
	Leaf-on	18.8 (0.41)		

Biomass

H_{GVH} and biomass (Figure 3A) had only weak correlation but the relationship was still significant ($R^2 = 0.11$, $p < 0.01$). Residual standard error (RSE) was 19.1 t/ha (22 %). Figure 3B shows that H_{ALS} is well correlated to biomass, which was calculated for each GVH pixel in Aegviidu test site and there is a strong linear relationship ($R^2 > 0.6$, $p < 0.01$). RSE for H_{ALS} and biomass relationship was 12.1 t/ha (14 %). Similar results were found in Laeva test site, but as the H_{GVH} relations to H_{ALS} and H_{FI} were weaker compared to Aegviidu (Figure 2), the biomass to H_{GVH} relationship was also weaker ($R^2 < 0.1$, $p < 0.01$).

Discussion

The goal of this study was to validate the spaceborne lidar based vegetation height map product in two contrasting hemiboreal forest test sites and validate how forest height estimated from spaceborne lidar is applicable for biomass estimation. Such products are viable for large forested areas in Eastern Europe, where access to ALS or FI data is limited.

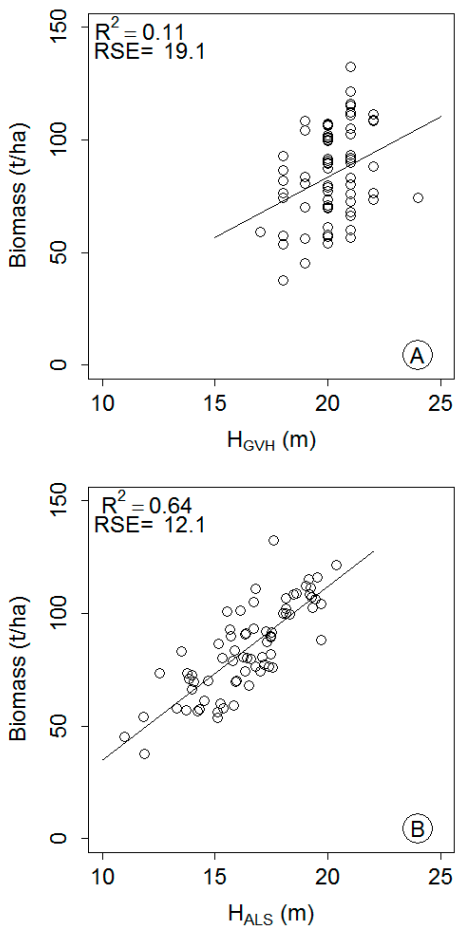

Figure 3. The biomass of forest trees calculated using Repola (2008, 2009) models in Aegviidu test site in relation to H_{GVH} (A) and H_{ALS} (B)

Forest height from global vegetation height map H_{GVH} showed weak correlations on pixel based comparison with FI data and ALS data based forest heights and this can be due to several reasons.

Firstly, there is difference in forest height definition: Simard et al. (2011) modelled the top canopy height whereas in our dataset the average forest height was available.

Secondly, part of the scatter in the relationships could be due to geometric inaccuracy and resampling. The forest stand border errors in forest inventory map are known to be in average about 10 metres. The coordinate errors of the used *in situ* sample plots for estimating the forest height model for ALS point cloud samples were also with up to 10 m location errors. However, much larger position errors with the size of about half a pixel (250...500 m) may be present in the coarse spatial resolution global GVH map. There is also an influence to H_{GVH} calculated from additional gap filling procedure via MODIS data, as MODIS single observation location is known to have substantial differences with the final gridded image as described by Tan et al. (2006).

Thirdly, some mismatch of H_{GVH} and H_{ALS} could be the result of the chosen percentile method for extracting data from the large ALS point clouds for each GVH pixel. To calculate ALS point cloud statistics for the large GVH pixels and small sample plots we selected the same 80-percentile method. The P_{80} based forest height model (1) was estimated from point clouds extracted for small circular plots and applied to large point clouds with the size of 50 hectares. We compared the average H_{ALS} for Laeva test site calculated from large GVH pixel size point clouds and alternatively from 20 by 20 m small point clouds. The mean forest height estimate was 2.8 metres lower when using small point cloud samples compared to large ALS point cloud subsets. So, in heterogeneous forests the point cloud sampling procedure has an influence to the forest height estimates.

Simard et al. (2011) also stated that the GVH product accuracy was lower in tall broadleaved forests (> 40 metres) with high canopy cover. Although the forest height in our test sites were usually lower than 30 m, this could also be the reason for weaker correlations in Laeva test site, which is dominated by broadleaved forest with high canopy cover. The explanation for the 2.8 metres smaller average height in leaf-off compared to leaf-on datasets in Laeva (Table 3) can also be caused by the dominance of deciduous forests in Laeva, as such difference in test site average height for Aegviidu was not found. Another possible reason for differences could be due to the time difference in data acquisition – the GLAS data was from 2005 and ALS scanning for Laeva was done in 2013.

Our analysis showed that the forest height range of H_{GVH} was narrower than the range of H_{ALS} or H_{FI}. We excluded at the beginning the GVH pixels with large disturbances to exclude outdated H_{FI}, but this resulted in removing also a substantial part of the young forests with smaller height and the forest height range was due to that narrower. Further tests proved that the removal of the filters didn't increase H_{GVH} height variation meaning that the height estimates for forest lower than 15 m are problematic for this GVH map in managed hemiboreal forests. However, Simard et al. (2011) modelled canopy top height and if we take in consideration that the 50 hectare GVH pixels are heterogeneous (average stand size in our test site is 2 hectares) then the GVH map values could be to some extent correct, since within 50 ha of forest land in Laeva or Aegviidu the occurrence of a high forest patch is common. To reduce the error caused by the heterogeneous landscapes we also applied the filter of forest land cover over 75 percent which improved the height correlations of H_{FI} and H_{ALS} but still gave no significant improvement on H_{GVH} to H_{FI} or H_{ALS} correlations. The large pixel based sampling error could be solved by using smaller pixel size.

If carefully validated, such wall-to-wall vegetation height maps could be well used for biomass and carbon monitoring, especially in areas where FI and ALS data are not available. As shown in Figure 3 GVH pixel based H_{ALS} had a strong linear correlation to biomass with a RSE of 12 t/ha. When we compare pixel level H_{GVH} and biomass relationship the results showed only a weak correlation with a 19 t/ha error. The spaceborne lidar based biomass estimation could also be improved by using forest cover (Sexton et al. 2013, Langanke 2013) maps additionally to the vegetation height maps.

To make a better error analysis of H_{GVH} estimates, we propose that next versions of global vegetation height maps must incorporate data quality description layer similarly to MODIS products with information of the number of GLAS measurements within the pixel and applied gap filling producers. In addition to ALS synthetic aperture radar (SAR) could be used for H_{GVH} validation or development, since SAR coherence has been found to have a strong relationship to ALS based forest height estimates (Olesk et al. 2015). There is a regular ALS scanning done by Estonian Land Board covering 1/4 of Estonia each year in spring and 1/5 of Estonia in summer, which could be a valuable data for testing the next versions of GVH or other similar products. Simard et al. (2011) show that GLAS data cover decreases with increasing latitude of geographic location. Our two test sites, Laeva and Aegviidu, are located almost at the limit of the GLAS data cover. Some additional test sites from Finland, Latvia and Lithuania could provide a latitudinal gradient for validating the next versions of GVH maps.

Conclusion

Based on this research we can conclude that the global vegetation height map (Simard et al. 2011) is not well applicable for forest height estimation in managed mixed species hemiboreal forests. Comparison on a pixel basis showed only weak correlation between H_{GVH} and H_{ALS} ($r < 0.25$, $p < 0.01$) and H_{GVH} to H_{FI} ($r < 0.2$, $p < 0.01$). Average forest height from GVH map was similar to H_{ALS} except in deciduous forests in spring. Mean height of GVH pixel is underestimated by 3 m from ALS data when sampling by small e.g. 10 m radius subsets instead of 50 ha subset.

Biomass estimates had a strong linear correlation to H_{ALS}, so in the future global vegetation height products, if carefully validated, could be used directly for biomass estimates, as similar correlations were shown for H_{GVH} and biomass relationship. The global vegetation height maps could also be improved by having a smaller pixel size, which would reduce the heterogeneity inside a pixel and additional forest cover maps would improve biomass estimates.

To improve the validation of such products, these maps should also include an additional layer showing pixel data quality and information on the number of used GLAS pulses per pixel.

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