How to consider the effects of time of day, beam strength, and snow cover in ICESat-2 based estimation of boreal forest biomass?

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1. Introduction

The launching of two novel spaceborne lidar sensors back in 2018 provided scientists with new data sources for global monitoring of forest above-ground biomass (AGB). The GEDI (Global Ecosystem Dynamic Investigation) sensor was mounted on the international space station and does not acquire data from the boreal forest zone above 52°N (Dubayah et al. 2020). However, the ICESat-2 (Ice, Cloud and land Elevation Satellite 2) is in polar orbit and thus provides plenty of data from boreal forests (Markus et al. 2017). The ICESat-2 ATLAS (Advanced Topographic Laser Altimeter System) is a profiling lidar sensor that provides strip samples of terrain height measurements using multiple beams. Despite being primarily designed for snow and ice monitoring, ICESat-2 can also provide relatively accurate canopy height observations (Neuenschwander et al. 2020) that can be used to predict forest biomass (Narine et al. 2020).

Construction of ICESat-2 based AGB models for boreal forests requires consideration of several effects that may influence the observed accuracy. The ATLAS is a photon-counting lidar that operates at 532 nm wavelength and is therefore subject to solar noise photons that must be omitted by filtering (Popescu et al. 2018). Data collected in sunlit conditions inherently has more noise photons than night data, which could hamper their simultaneous use. The ATLAS has three strong and three weak lidar beams, and the weak beams may have a considerably poorer capability to observe canopy heights than the strong beams (Neuenschwander et al. 2020). In addition, boreal forests have snow cover during the winter. Snow on the forest floor and trees increases the reflectance at the 532 nm wavelength compared to summer conditions. If there is plenty of snow, the allometries between AGB and observed canopy heights could also be different, if the ground elevation is estimated from the ATLAS data.

Our objective is to investigate how the effects of time of day, beam strength and snow cover should be considered when constructing models for boreal forest AGB estimation using ICESat-2 data.

2. Data and methods

Our study site is a 60 × 50 km forest area located in Eastern Finland. The dominant tree species are Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and birches (*Betula* spp.). The snowy season typically lasts from late November to late April.

We used airborne laser scanning (ALS) data and field plots acquired for an operational forest inventory in 2019. A total of 797 field plots with AGB ≥ 5 t ha^{-1} were measured and used as training data. The ground AGBs were predicted by tree level allometric models that used diameter and height as inputs (Repola 2008, Repola 2009). The ALS data were collected 7 June – 9 July 2019 using a Leica ALS 80HP scanner at 1700 m above ground level, which resulted in a nominal pulse density of 5 m^{-2}. The publicly distributed data was however resampled to 0.5 pulses m^{-2}, which was still sufficient for AGB modelling using the area-based approach. The public ALS data were used to compute a set of

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canopy height distribution variables for the field plots. We also extracted a set of spectral variables from an atmospherically corrected Sentinel-2 satellite image obtained 14 June 2019. These data were used to construct a model that was applied to predict reference AGBs for the ICESat-2 tracks in the study area. The model was constructed using regression analysis, and its predictors were selected using optimization by simulated annealing (Packalen et al. 2012). The final model included four predictor variables (two ALS, two Sentinel-2) and its relative root mean square error (RMSE) was 20.2%.

We used a total of five ICESat-2 passes from 2019 (2 and 22 February, 22 June, 18 and 22 August) to obtain a set of predictor variables representing day and night conditions with and without snow. We used ATL03 geolocated photon product (version 3), but the noise photons were removed based on the ATL08 land and vegetation product. A set of 15 x 90 m segments were placed at the ICESat-2 ground tracks. Each segment consisted of four 15 x 15 m cells, for which the reference AGBs were predicted using the ALS and Sentinel-2 data. The predicted AGBs were aggregated for the segments, and the segment AGBs were further used as reference values in ICESat-2 based AGB modelling.

The noise-filtered ATL03 photons located within the segments were used to compute a set of canopy height distribution variables based on normalized photon heights. The processing chain was similar to the ALS data. The variables included average height (avg), average square height (qav), standard deviation of height (std,) canopy height percentiles (p1, p5,…, p99), and canopy density percentiles (d1, d5, …, d99). Based on these variables, we constructed separate regression models for each of the eight ATL03 subsets (day/night, weak/strong beam, snow/no-snow), as well as a combined model where the time of day (night), beam strength (strong) and snow cover (snow) were included as dummies. In addition to the canopy height distribution variables listed above, sun elevation (sunelev), snow depth (snowdepth) and photon count (count) within the segment were used as additional predictors.

3. Results and discussion

In terms of RMSE (Table 1), winter models (RMSE 27–35%) showed smaller errors than summer models (34–61%). In winter conditions also the weak beam data were useful in AGB estimation, as the respective RMSEs were only 1–2 percent points larger than the strong beam RMSEs. With winter data, the day models also showed smaller RMSEs (27–28%) than night models (33–36%). However, the current winter results only represent the snow and weather conditions during the two ICESat-2 passes in February 2019. Weather could explain the observed differences, as the winter night data set had 20% of the photons removed as noise, which was above average for night conditions.

Table 1. The AGB models constructed for the different subsets based on the ATL03 data in the order of increasing RMSE.

Season	Time of day	Beam	n	Model	R^2	RMSE
Winter	Day	Strong	1150	$\sqrt{AGB} = 6.27 - 3.69E\text{-}3 \sqrt{count} + 0.13\ p99 + 2.62 \sqrt{avg}$	0.79	27%
Winter	Day	Weak	198	$\sqrt{AGB} = 23.99 + 0.14\ p99 - 1.31 \sqrt{count}$	0.73	28%
Winter	Night	Strong	901	$\sqrt{AGB} = 40.65 - 0.22 \sqrt{count} + 4.10 \sqrt{avg} - 4.60 \sqrt{snowdepth}$	0.82	33%
Summer	Night	Strong	2728	$\sqrt{AGB} = 0.76 + 4.21 \sqrt{avg} - 0.22 \sqrt{qav}$	0.77	34%
Winter	Night	Weak	874	$\sqrt{AGB} = -110.26 - 3.04\ sunelev - 0.34\ p60 - 0.57 \sqrt{count} + 3.93 \sqrt{avg}$	0.75	35%
All	All	All	7158	$\sqrt{AGB} = 2.62 - 1.42\ night - 0.67\ strong + 2.08\ snow + 3.54 \sqrt{avg}$	0.68	41%
Summer	Day	Strong	312	$\sqrt{AGB} = -21.65 + 3.78\ sunelev + 0.84\ std + 0.26\ p90 + 0.16 \sqrt{count}$	0.77	50%
Summer	Night	Weak	433	$\sqrt{AGB} = 1.69 + 3.02 \sqrt{avg}$	0.61	56%
Summer	Day	Weak	177	$\sqrt{AGB} = -55.50 + 10.73\ sunelev + 0.026\ p99 + 0.61\ b95 - 5.88 \sqrt{b80}$	0.39	61%

Without snow, only the strong beam night data provided an RMSE that was comparable to winter models (34%). Strong beam day data also performed well if measured by R^2 (0.77), but its RMSE was large (50%) as the sampled forest area had a small average AGB. Weak beam summer models had the poorest relative RMSEs (56–61%). The model that combined all data sets had larger RMSE than most of the individual models (41%) despite having time of day, snow cover and beam strength as statistically significant dummy variables.

4. Conclusions

The effects of snow cover and beam strength should be considered when constructing ICESat-2 based models for boreal forest AGB. It is better to construct separate models for different beams and snow conditions instead of merging everything into a single model. ATL03 data from snowy forests is well suited for AGB modelling, probably because of the increased reflectance at 532 nm, which makes weak beam data also usable. Time of day only had a clear effect on weak beam data without snow, where the night data provided a considerably smaller RMSE. In other cases, it could be possible to utilize both day and night data in a single model without compromising accuracy, at least if time of day is included as a predictor variable. The noise photon classification contained in the ATL08 product seemed sufficient for AGB modelling, although alternative noise filtering algorithms should also be tested in the future.

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