Remote Sensing of Environment 158 (2015) 95–109

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

The uncertainty of biomass estimates from modeled ICESat-2 returns across a boreal forest gradient

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ARTICLE INFO

Article history:
Received 24 February 2014
Received in revised form 3 September 2014
Accepted 24 October 2014
Available online xxxx

Keywords:
Ecotone
LiDAR
Radiative transfer model
Forest biomass
Uncertainty
Spacebourne

ABSTRACT

The Forest Light (FLIGHT) radiative transfer model was used to examine the uncertainty of vegetation structure measurements from NASA's planned ICESat-2 photon counting light detection and ranging (LiDAR) instrument across a synthetic *Larix* forest gradient in the taiga–tundra ecotone. The simulations demonstrate how measurements from the planned spaceborne mission, which differ from those of previous LiDAR systems, may perform across a boreal forest to non-forest structure gradient in globally important ecological region of northern Siberia. We used a modified version of FLIGHT to simulate the acquisition parameters of ICESat-2. Modeled returns were analyzed from collections of sequential footprints along LiDAR tracks (link-scales) of lengths ranging from 20 m–90 m. These link-scales traversed synthetic forest stands that were initialized with parameters drawn from field surveys in Siberian *Larix* forests. LiDAR returns from vegetation were compiled for 100 simulated LiDAR collections for each 10 $Mg \cdot ha^{-1}$ interval in the 0–100 $Mg \cdot ha^{-1}$ above-ground biomass density (AGB) forest gradient. Canopy height metrics were computed and AGB was inferred from empirical models. The root mean square error (RMSE) and RMSE uncertainty associated with the distribution of inferred AGB within each AGB interval across the gradient was examined.

Simulation results of the bright daylight and low vegetation reflectivity conditions for collecting photon counting LiDAR with no topographic relief show that 1–2 photons are returned for 79%–88% of LiDAR shots. Signal photons account for ~67% of all LiDAR returns, while ~50% of shots result in 1 signal photon returned. The proportion of these signal photon returns do not differ significantly ($p > 0.05$) for AGB intervals >20 $Mg \cdot ha^{-1}$. The 50 m link-scale approximates the finest horizontal resolution (length) at which photon counting LiDAR collection provides strong model fits and minimizes forest structure uncertainty in the synthetic *Larix* stands. At this link-scale AGB >20 $Mg \cdot ha^{-1}$ has AGB error from 20–50% at the 95% confidence level. These results suggest that the theoretical sensitivity of ICESat-2 photon counting LiDAR measurements alone lack the ability to consistently discern differences in inferred AGB at 10 $Mg \cdot ha^{-1}$ intervals in sparse forests characteristic of the taiga–tundra ecotone.

1. Introduction

1.1. Global relevance of the taiga–tundra ecotone

At the northern edge of the boreal forest in the taiga–tundra ecotone (TTE), vegetation cover and structure is changing (Elmendorf et al., 2012; Epstein et al., 2013; Myers-Smith et al., 2011; Kharuk et al., 2013; Ropars & Boudreau, 2012). These changes can be subtle yet occur across broad scales, and can alter the magnitude and direction of biome-level and continental scale feedbacks to climate (Bonan, 2008; Bonfils et al., 2012; Chapin, Sturm, & Serreze, 2005; Chapin et al., 2000; Lawrence & Swenson, 2011; Loranty & Goetz, 2012; Loranty et al., 2011, 2013; Myers-Smith et al., 2011; Pearson et al., 2013; Swann, Fung, Levis, Bonan, & Doney, 2010).

Broad-scale, but spatially discontinuous and heterogeneous, changes in forest structure are expected in northern Siberia, where the TTE reaches its northern-most limit extending above 72°N (Bondarev, 1997). At specific sites in the TTE canopy closure and expansion of *Larix* in tundra have been observed (Kharuk, Ranson, Im, & Naurzbaev, 2006). Evidence shows that dark-needle conifers have begun moving into *Larix* forests

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http://dx.doi.org/10.1016/j.rse.2014.10.029
0034-4257/

and woodlands (Kharuk, Dvinskaya, Ranson, & Im, 2005). Observed at broad-scales, the patterns formed by the smaller plot-scale changes (Devi et al., 2008; Elmendorf et al., 2012; Forbes, Fauria, & Zetterberg, 2010; Harsch, Hulme, McGlone, & Duncan, 2009; Mazepa & Devi, 2007; Myers-Smith et al., 2011; Shiyatov & Mazepa, 2012; Vaganov & Kirdyanov, 2009) demonstrate their overall magnitude, uniformity, spatial characteristics and links with other landscape characteristics across a biome. Such characteristics include the extent of continuous permafrost, which across northern Siberia influences the distribution of vegetation (Lloyd, Bunn, & Berner, 2010; Schulze et al., 2012; Sugimoto, Yanagisawa, Naito, Fujita, & Maximov, 2002; Tchebakova, Parfenova, & Soja, 2009; Zhang, Yasunari, & Ohta, 2011). The strength and timing of a climate feedback from permafrost-bound carbon is a function of vegetation structure (Epstein et al., 2004; Jorgenson et al., 2010; Lawrence & Swenson, 2011; Schaefer, Zhang, Bruhwiler, & Barrett, 2011). Model projections of this feedback to climate, accounting for vegetation characteristics, suggest a central role for high northern latitude vegetation structure in determining the magnitude of changes to the global carbon cycle (Schaefer et al., 2011).

These subtle changes in vegetation structure and patterns in the high northern latitudes across broad scales and acute climate changes in northern Siberia highlight the need for both synoptic and spatially detailed remote monitoring of vegetation. Furthermore, the possibility that subtle changes in vegetation structure may significantly alter climate feedbacks warrants improved characterization of how uncertainty in vegetation measurements varies with extent and structure, particularly in the sparse *Larix* forest gradients of the TTE where non-uniform vegetation changes may be converging.

1.2. Forest structure in northern Siberia

Forest stands within the TTE of northern Siberia have an over-story that is often exclusively *Larix*, are sparse and short in stature, and form the northern limit of forest vegetation (Abaimov, 2010). Stand structure in this region is heavily influenced by the presence of permafrost. *Larix* stands sampled along the Kotuykan River in 2008 at flat or gently sloping north and south facing slopes show that >90% of trees are <10 m in height (Kharuk et al., 2013; unpublished data). Mean tree heights of *Larix gmelinii* generally do not exceed ~12 m for stands underlain with continuous permafrost and varying active layer depths (Osawa & Kajimoto, 2010; Usoltsev, Koltunova, Kajimoto, Osawa, & Koike, 2002). For these stands, the maximum above-ground biomass density (AGB) is approximately 100 Mg ha^{-1}. This depends on stand age, tree density and local site conditions, and AGB potential generally decreases from south to north, following a latitudinal gradient (Osawa & Kajimoto, 2010).

1.3. LiDAR remote sensing of vegetation

Light detection and ranging (LiDAR) has become widely used for measuring and monitoring vegetation characteristics because of its potential sensitivity to subtle vegetation structural differences (Naesset & Bjerknes, 2001; Popescu et al., 2011; Wasser, Day, Chasmer, & Taylor, 2013; Whitehurst, Swatantran, Blair, Hofton, & Dubayah, 2013), and its availability on platforms that have sampled across a range of scales (Næsset & Nelson, 2007; Nelson et al., 2009). LiDAR sensors are often deployed as airborne systems (LVIS; Blair, Rabine, & Hofton, 1999, G-LiHT; Cook et al., 2013) but have also collected data globally from space (ICESat-GLAS; Abshire et al., 2005). Satellite-based LiDAR collections offer consistent, synoptic sample measurements of surface characteristics across broad scales. While the only free-flying satellite-based LiDAR instrument, to date, was designed primarily to measure ice, ICESat-GLAS has been used in concert with passive optical satellite data to provide regional-global scale estimates of timber volume, vegetation carbon density, above-ground biomass density, and vegetation height (Baccini, Laporte, & Goetz, 2008; Lefsky, 2010; Los et al., 2012; Neigh et al., 2013; Nelson et al., 2009; Simard, Pinto, & Fisher, 2011). These measurements have been made despite GLAS footprints being ~50–60 m in diameter, spaced ~170 m along track (extending to 86° north and south), and covering only a small fraction of the vegetated land surface. The accuracy of vegetation height measurements from ICESat-GLAS vary depending on a number of factors including vegetation type, slope and measurement scale, and can range from ~3 m–12 m (Duncanson, Niemann, & Wulder, 2010; Lefsky et al., 2005; Rosette, North, & Suarez, 2008).

LiDAR sensors vary in how they measure vegetation. Waveform (i.e., pulse-limited) LiDAR sensors digitize the vertical distribution of vegetation structure within a footprint by recording the total energy returned from a single transmitted pulse for fixed vertical bins. Discrete return LiDAR provides ~3–5 returns for each LiDAR pulse based upon the intensity of returned energy (Evans, Hudak, Faux, & Smith, 2009). Recently, micropulse (photon counting) LiDAR technology has emerged as a means for remote sensing of vegetation structure. For vegetation, this technology yields point clouds that represent vegetation height measurements that are derived from individual photon returns collected from many low-energy LiDAR pulses in rapid succession (Herzfeld et al., 2013). These photon returns can be spatially aggregated to create histograms of the vertical distribution of returns for a given area, similar to data provided by a LiDAR waveform. Each sensor's ability to measure and map vegetation structure depends on multiple factors including sensor design, data collection schemes (timing and spatial characteristics of the measurement), and vegetation characteristics (type, density, health).

The spaceborne LiDAR on the ICESat-2 satellite, scheduled to launch no earlier than 2017, will feature a multiple-beam (a combination of stronger and weaker beams) photon counting LiDAR instrument (ATLAS). The initial data collection scheme for a given beam on the ATLAS sensor noted that photons will be collected for a 10 m diameter footprint at 70 cm along-track spacing (Abdalati et al., 2010), however updated schemes have increased the footprint size. The exact position of each photon from within the footprint will not be known. For sparse forest stands in the TTE, a single footprint's measurement will be insufficient for characterizing vertical vegetation structure within that footprint and for inferring vertical vegetation characteristics outside the footprint, particularly as vegetation heterogeneity increases. LiDAR collection schemes for characterizing various types of forest stands (e.g., the way in which photon returns are aggregated spatially) may help improve vegetation structure measurements as well as improve understanding of how these measurements change with vegetation characteristics.

Given the sparse density of trees in TTE forests, the photon returns within a single footprint are unlikely to come from a tree, particularly the highest portion of the canopy. This issue of under-sampling the top portion of forest canopies is common for LiDAR measurement of forest structure (Kaartinen et al., 2012; Næsset, 2011; Nelson, Krabill, &

Table 1
Summary of the parameters used by FLIGHT to simulate photon transport from the planned ATLAS instrument.

Parameter	Value
Operational altitude (m)	496,000
Wavelength (nm)	532
Telescope diameter (m)	0.8
Laser pulse energy (μJ)	164
Laser footprint diameter (m) ($1/e^2$)	10
Telescope field of view (μrad)	83.3 (40 m)
Detector efficiency @ 532 nm	15%
Swath width (km)	±3
Beam divergence (rad)	5.04032E−06
Pulse duration (ns)	0.375
Samples·m^{-1}	1.42857