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Quantitative assessment of the impact of typhoon disturbance on a Japanese forest using satellite laser altimetry

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ABSTRACT

Spaceborne light detection and ranging (LiDAR) sensors can accurately observe forest parameters, such as canopy height and forest biomass. In this study, we investigated the potential of spaceborne LiDAR to quantify the effects of forest disturbances caused by typhoons on Hokkaido Island, Japan, after typhoon Songda in 2004. We developed a model to estimate canopy height from the Geoscience Laser Altimeter System (GLAS) of the Ice Cloud and land Elevation Satellite. GLAS waveforms are broadened by slopes ("pulse broadening"), so we used the lead10 and trail10 values (edge extents referring to 10% and 90% of the cumulative energy returned) to correct for this effect, because they were the parameters most strongly correlated with pulse broadening. We developed the estimation model by dividing GLAS data between gentle and steep slopes, using an empirically determined threshold, and obtained a root-mean-square error of 3.5 m for canopy height. We then applied the model to GLAS data in the area damaged by typhoon Songda to estimate changes in canopy height caused by the typhoon. We used a wind damage map produced in a previous study to identify the damage severity. The model showed that canopy height decreased by an average of 2.7 ± 1.8 m (95% confidence interval) in heavily damaged areas. The canopy height decreased most in coniferous forests, and especially in Japanese larch forests, that they have very shallow roots. We also assessed the geographic factors that most strongly influenced wind damage risk by means of multivariate analysis. We found serious damage in areas with a gentle slope that sustained strong winds. Understory plants and topography type also affected the risk. Our results show that spaceborne LiDAR can be used to quantify the severity of wind damage caused by forest disturbances, thereby providing guidance for forest management.

1. Introduction

Forest ecosystems can become net carbon sources after a disturbance and a net sink during recovery and growth. The carbon budget of forests therefore represents a balance between these processes. Many studies have suggested that disturbances, including logging, insects, diseases, fire, and wind, can strongly affect a forest's long-term carbon budget (e.g., Liu et al., 2011). FAO (2010) reported that insect infestations disturbed about 1.6% of the global forested area annually, versus 0.2% for disease and 0.7% for fire, based on data from many countries of the world. However, they also reported that information on other disturbances (e.g. wind, floods, and drought) was highly sporadic, and because it included a broad range of causative agents, it was not possible to obtain an aggregate value. Forest disturbances are often difficult to detect and their effects are difficult to evaluate, and this causes uncertainty in estimates of forest carbon stocks (Fagan & Defries, 2009; Houghton, Hall, & Goetz, 2009). To solve this problem, it is necessary to develop solutions that can accurately estimate the carbon losses and gains caused by forest disturbances and subsequent recovery. The availability of technology for monitoring forest disturbances is expected to play an important role in accurate assessment of forest carbon budgets.

Field studies have been conducted as a traditional method to observe the effects of forest disturbances, but they are time-consuming and labor-intensive. Remote sensing can solve these problems for observation of disturbances over large areas (Frolking et al., 2009). To monitor carbon losses caused by forest disturbances, a combination of data that captures both the spatial extent and the severity of the disturbances is required (Liu et al., 2011). Long-standing satellite optical systems such as Landsat, NOAA/AVHRR, and MODIS have provided sufficient spatial and historical coverage to monitor yearly changes in forest health (Lutz, Washington-Allen, & Shugart, 2008). Although optical sensors can observe the extent and location of disturbances, they have limitations for observing the *severity* of the disturbances. Synthetic-aperture radar (SAR) has been used to measure forest biomass, but its sensitivity to biomass becomes saturated in forests with high biomass (Shugart, Saatchi, & Hall, 2010). In contrast, light detection and ranging (LiDAR) is an active sensor technology that potentially overcomes the saturation problem (Mitchard et al., 2012), and it can therefore be used to quantify canopy height and aboveground forest biomass.

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The Geoscience Laser Altimeter System (GLAS) on NASA's Ice Cloud and land Elevation Satellite (ICESat) was the only spaceborne LiDAR system capable of measuring land surfaces (Abshire et al., 2005; Schutz, Zwally, Shuman, Hancock, & DiMarzio, 2005). GLAS observed most of the world between 2003 and 2009. It was developed primarily to monitor polar ice sheets, but it has also been used for observations of forest parameters such as canopy height and aboveground biomass (Wang, Cheng, & Gong, 2011). GLAS recorded the laser pulse returned from the Earth's surface as a waveform, and canopy height or forest biomass can be estimated by analyzing the information contained in the waveform of the returned signal (e.g., Lefsky et al., 2005). Several researchers have used GLAS data to observe forest disturbances. Ranson, Sun, Kovacs, and Kharuk (2004) investigated the characteristics of GLAS waveforms from forests disturbed by insects or fire. Goetz, Sun, Baccini, and Beck (2010) estimated the canopy height decreases after fire, and Dolan et al. (2011) estimated canopy height decreases following hurricane Katrina. However, there have been few other studies that used GLAS data to observe forest disturbances.

In the present study, we examined the potential of spaceborne LiDAR to quantify the impact of forest disturbance caused by typhoons. To do so, we developed a methodology to estimate canopy height from GLAS data that would be suitable for our study area, then we used this method to estimate changes in canopy height caused by a typhoon. In addition, we identified the geographic factors that could affect wind damage to show the potential effectiveness of spaceborne LiDAR for risk assessment. Typhoons are tropical cyclones that develop in the Northwest Pacific Ocean and are similar to hurricanes. Typhoons represent a major forest disturbance in East Asia, including Japan (Fischer, Marshall, & Camp, 2013), so being able to forecast their risk can provide important guidance for forest management.

2. Methods

2.1. Study area

Hokkaido Island is in northern Japan between 41°N and 46°N latitude (Fig. 1), and has a cool–temperate humid climate. Forests on Hokkaido cover 5,543,000 ha, of which 30% are artificial forest and 70% are natural forest (Forestry Agency of Japan, 2014). The artificial forests mainly consist of conifers such as Sakhalin fir (*Abies sachalinensis*) and Japanese larch (*Larix kaempferi*). The natural forests consist of conifers such as Sakhalin fir and Yezo spruce (*Picea jezoensis*), and broadleaved species such as Japanese oak (*Quercus crispula*). Typhoons rarely strike Hokkaido, because many typhoons lose strength and change into extratropical storms before approaching Hokkaido. The normal annual frequency of typhoon approach is 7.4 times in Okinawa (southern Japan), 3.1 times in Kanto (central Japan), and 1.8 times in Hokkaido (Japan Meteorological Agency, 2014). However, not all typhoons strike the land. Therefore, forests in Hokkaido are rarely affected by typhoons as compared with other regions of Japan.

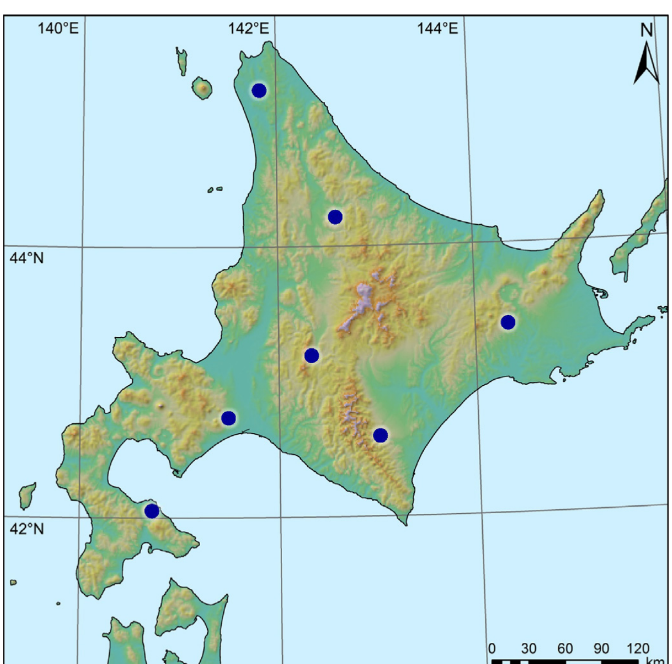

Fig. 1. Locations of the seven study sites on Japan's Hokkaido Island.

Typhoon Songda hit Hokkaido on 8 September 2004, and it caused serious wind damage to 37,000 ha of forest (this is totalized value of municipalities' reports; Hokkaido Forestry Research Institute, 2004). The typhoon was accompanied by extremely strong winds. Previous records for the maximum instantaneous wind speed were broken at more than half of the meteorological stations on Hokkaido, and the maximum value reached 51.5 m s^{-1} (Japan Meteorological Agency, 2004). The Hokkaido Forestry Research Institute (2004) reported that damaged areas were mostly located in artificial forests of conifers, and that uprooting and stem breakage were common. They also reported extremely serious damage around Tomakomai, in southwestern Hokkaido, and about 30% of the damaged area on Hokkaido was located in Tomakomai City and its neighbor, Chitose City.

We chose a study area to assess the effects of typhoon Songda at Tomakomai. Specifically, we focused on the national forests in Tomakomai City, Chitose City and Eniwa City (three neighboring cities), where these forests covered 55,544 ha (Ministry of Agriculture, Forestry and Fisheries, Japan, 2012). The study area is located on the slope of an active volcano, with some erosion channels and river ravines. We developed a model to estimate canopy height from GLAS data and used it to assess the impact of the typhoon. We also selected an additional six sites throughout Hokkaido (Fig. 1), because it was not possible to obtain sufficient ground-truthing data only at the Tomakomai site. There were no significant differences in tree species composition between the Tomakomai site and the other six sites based on the vegetation map of the Ministry of the Environment, Japan (http://www.biodic.go.jp/kiso/fnd_f_vg.html). Therefore, a model for estimating canopy height that was developed for all of Hokkaido's forests based on data from all seven sites should also be suitable for the Tomakomai site.

2.2. Data collection

We collected airborne LiDAR data at each of the seven sites, and used this data to ground-truth canopy height estimates from the GLAS data. Table 1 summarizes the airborne LiDAR data. The cloud of ground points extracted from the original point cloud was converted into a digital terrain model (DTM) with 2-m resolution. The height of features could be estimated by calculating the height differences between the original point cloud and the DTM, and it represented the canopy height in the forested area. Such data are usually called a canopy-height model (CHM), and we used these as the ground-truth data.

Table 1
Summary of the airborne LiDAR data used to ground-truth the canopy height estimates produced using the GLAS data.

Site	Acquisition year/month	Sensor	Average pulse density (m^{-2})
Horonobe	2006/10	Optech/ALTM3100DC	1.0
Nayoro	2006/10	Optech/ALTM3100DC	1.2
Kushiro	2006/5-10	Optech/ALTM3100DC	1.0
Furano	2006/8-9	Optech/ALTM3100DC	1.8
Obihiro	2006/5	Optech/ALTM3100DC	1.2
Tomakomai	2008/10-11	Leica/ALS50	2.8
Mori	2000/10	Optech/ALTM1225DC	0.8