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Influence of terrain model smoothing and flight and sensor configurations on detection of small pioneer trees in the boreal–alpine transition zone utilizing height metrics derived from airborne scanning lasers

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A B S T R A C T

It has been suggested that airborne laser scanning (ALS) with high point densities could be used to monitor changes in the alpine tree line. The overall goal of this study was to assess the influence of ALS sensor and flight configurations on the ability to detect small trees in the alpine tree line and on the estimation of their heights. The study was conducted in a sub-alpine/alpine environment in southeast Norway. 342 small trees (0.11–5.20 m tall) of Norway spruce, Scots pine, and downy birch were precisely georeferenced and measured in field. ALS data acquired with two different instruments and at different flying altitudes (700–1130 m a.g.l.) with different pulse repetition frequencies (100, 125, and 166 kHz) were collected with a point density of all echoes of 7.7–11.0 m^{-2}. For each acquisition, three different terrain models were used to process the ALS point clouds in order to assess the effects of different preprocessing parameters on the ability to detect small trees. Regardless of acquisition and terrain model, positive height values were found for 91% of the taller trees (>1 m). For smaller trees (<1 m), 29–61% of the trees displayed positive height values. For the lowest repetition frequencies (100 and 125 kHz) in particular, the portion of trees with positive laser height values increased significantly with increasing terrain smoothing. For the highest repetition frequency there were no differences between smoothing levels, likely because of large ALS measurement errors at low laser pulse energy levels causing a large portion of the laser echoes to be discarded during terrain modeling. Error analysis revealed large commission errors when detecting small trees. The commissions consisted of objects like terrain structures, rocks, and hummocks having positive height values. The magnitude of commissions ranged from 709 to 8948% of the true tree numbers and tended to increase with increasing levels of terrain smoothing and with acquisitions according to increasing point densities. The accuracy of tree height derived from the ALS data indicated a systematic underestimation of true tree height by 0.35 to 1.47 m, depending on acquisition, terrain model, and tree species. The underestimation also increased with increasing tree height. The standard deviation for the differences between laser-derived and field-measured tree heights was 0.16–0.57 m. Because there are significant effects of sensor and flight configurations on tree height estimation, field calibration of tree heights at each point of time is required when using airborne lasers for tree growth monitoring.

1. Introduction

As a result of global warming, the world's climate will undergo distinct alterations over the coming decades leading to rapid changes in basic growth factors for trees and other vegetation, such as temperature and precipitation. Changes in these growth factors are expected to display different patterns in different regions. Regionalized weather predictions for example for Norway indicate an increase in mean annual temperature by 0.5–2.5 °C over the next 40 years (Anon., 2009). This will influence significantly the boreal forest and its transition zones, leading to an increase in productivity (Zheng et al., 2002). Because the mountain forest, which is found in the transition zones between the boreal forest and the alpine region appears in an area where the trees exist close to their tolerance limit in terms of temperature, these areas are characterized by steep temperature-productivity gradients. Even a moderate increase in temperature may therefore lead to a rapid increase in the growth of existing trees (Kullman, 1986, 2007) as well as colonization of tree-less areas and migration of the alpine tree line (Danby & Hik, 2007). Thus, tree line alteration is considered an important indicator of climate change along with factors such as changes in fire regimes and in vegetation communities (Soja et al., 2007). Migration of the alpine tree line will also influence future carbon pools. A need therefore exists to monitor vegetation changes caused by natural and human-induced processes in these transitions zones (Callaghan et al., 2002).

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Capturing data for monitoring purposes over vast areas is expensive. So far, attempts to simplify ground-based procedures, save costs, and make them uniform over large areas have relied on remote sensing from space-borne platforms. Satellite remote sensing utilizing optical sensors has been the dominant technology, but such data have limited capabilities of detecting subtle changes in the vegetation over short time periods.

As far as effects of climate change on the boreal–alpine transition zone are concerned, at least three different processes need to be monitored, namely (1) detection of tree colonization in tree-less areas, (2) detection of tree mortality, and (3) estimation of tree growth of established trees. It is a challenging task to detect such changes over short time periods with any remote sensing technique. However, recently it has been demonstrated that laser remote sensing from airborne platforms represents a promising technology for precise estimation of biophysical parameters of trees and forests with high spatial and temporal resolution. Previous studies have indicated that tree removal as well as tree height growth of larger individual trees can be estimated with a RMSE of ~0.4 m using high-density airborne scanning laser data (~10 points per m^2) over a relatively short time period (five years) (Yu et al., 2004, 2006) or even shorter periods when average values over an area is considered (Næsset & Gobakken, 2005). In a forest with a height growth of around 0.3–0.4 m per year, Hopkinson et al. (2008) demonstrated that the height growth at a plot basis could be estimated from laser data over a three year period with a 10% uncertainty compared to "true" height growth. In a recent study, Wulder et al. (2007) used profiling airborne lasers to estimate changes in a boreal forest over a five year period along a 600 km long transect in Canada. They concluded that profiling laser was not capable of detecting local changes over such a short period. Rees (2007) used a scanning laser with relatively low density (~0.25 points per m^2) to characterize the spatial variations in vegetation structure in the arctic tree line in the northern part of Norway, and based on a preliminary investigation it was anticipated that airborne laser scanning could provide a means for detecting individual trees over hundreds of square kilometers. However, it should be noted that Rees (2007) used a minimum height of 2 m as the definition of a tree. Smaller trees were thus ignored.

In contrast to the studies mentioned above, Næsset and Nelson (2007) focused mainly on the smallest trees in the alpine tree line, i.e., trees ranging from <0.1 m and up to around 5 m in height. They addressed all the three monitoring challenges introduced above, namely detection of individual trees which is required for (1) monitoring of mortality and (2) colonization in tree-less areas, and (3) monitoring of growth, which is related to tree height estimation and changes in tree height over time. Using high-density data from laser scanning (~8 points per m^2), they reported a near 100% success in tree detection for trees that had reached a size corresponding to a tree crown diameter of about 1 m. The tree height was estimated with a precision of 0.1–0.7 m, but the height estimates were biased with an underestimation of 0.4–1.0 m depending on tree size. They also argued that for monitoring purposes it would make sense to estimate mean tree height and changes in mean tree height over a target area of a certain size, for example 12 ha which was the size of their trial area.

In an operational monitoring context with repeated measurement, say, every 5 to 10 years, it is likely that different sensors will be used on the different points of time. The rapid growth in the commercial market for services and products based on airborne laser scanning (ALS) has lead to a large portfolio of new instruments coming into the market. The commercial lifetime of these ALS instruments is normally quite short, often around 2–5 years. Different instruments have different properties that will influence the responses from the vegetation and thus the properties and the specific data values of the datasets derived from the data acquisition (Næsset, 2005, 2009). The sensor producers also tend to become less and less willing to share information with the scientific and user communities on sensor characteristics of great importance to vegetation measurements (Næsset, 2009). Examples of such characteristics are laser pulse energy levels and pulse properties, and algorithms used to trigger the echoes of a laser pulse reflected from the vegetation (Wagner et al., 2004), which have been shown to have an impact on vegetation characteristics as measured by lasers (Chasmer et al., 2006; Hopkinson, 2007; Næsset, 2005, 2009). It is also common practice to upgrade ALS instruments during the lifetime by increasing e.g. the pulse repetition frequency (Næsset, 2005) by replacing hardware and firmware components. Sensor properties of significant importance for vegetation measurements may even be altered by software upgrade and instrument calibration taking place in regular service and maintenance. Thus, if these sensor related factors are found to influence significantly on the basic features to be targeted in tree line monitoring, i.e., tree detection and tree height estimation of small trees, design of operational tree line monitoring systems must take these factors into account.

For larger trees it is well documented that sensors with differences in properties like energy levels and beam divergence, and even acquisitions with the same instrument but differences in e.g. flying altitude, pulse repetition frequency, and footprint size, may produce laser point clouds with different properties. Such differences will lead to differences in height distributions and thus in metrics of vegetation structure and —density, and will therefore also influence the biophysical properties estimated from the ALS data (Andersen et al., 2006; Chasmer et al., 2006; Goodwin et al., 2006; Holmgren et al., 2003; Hopkinson, 2007; Morsdorf et al., 2008; Næsset, 2004, 2005, 2009). It is not necessarily so that the magnitude of differences in data properties is the same for larger and small trees — at least as far as discrete return ALS sensors are concerned. It is therefore not straightforward to infer from experiences with large trees how different sensors and properties of the ALS acquisitions will influence the measurements of small trees. For tall trees, emitted laser pulses from a discrete return system could potentially produce multiple echoes as they penetrate through the canopy whereas small trees often are too short to trigger more than a single echo due to the minimum vertical separation between subsequent echoes, typically being in the range of 2–5 m. Different echo categories have different properties and are influenced differently by flight and sensor configurations (Chasmer et al., 2006; Hopkinson, 2007; Næsset, 2009). Furthermore, the distribution of biological material on different fractions (foliage, stem, branches) is very different in small and large trees. In large trees, it is likely that big branches sometimes will be the reflecting surface of a laser pulse. That is less likely to happen for small trees where the maximum branch thickness is, say, 1 cm.

Thus, the overall goal of this study was to assess the influence of sensor and flight specifications on the ability to detect small trees in the alpine tree line and on the estimation of their heights. The study by Næsset and Nelson (2007) revealed that the degree of smoothing when deriving the terrain model had a significant impact on tree detection rates and tree height estimation. For a small tree, a major portion of the biological matter with which a laser pulse interacts, is allocated so close to the ground level that a high degree of smoothing will tend to produce positive height values for echoes close to the ground whereas a low smoothing level will tend to include trees and other non-terrain objects in the terrain model, i.e., produce a height value of zero. The tree detection omission errors will therefore tend to increase with decreasing smoothing whereas the commission errors will tend to increase with increasing smoothing.

The specific objectives of this study were (1) to assess how different sensor and flight configurations influenced the success of detecting small trees in the alpine tree line and to evaluate how the ability to detect small trees was influenced by tree species, tree size, and degree of terrain smoothing. Further, (2) the accuracy of tree height estimation based on the ALS measurements for different configurations of the ALS acquisition was assessed, and it was evaluated how the height estimation for the different acquisitions was influenced by tree species and — size and terrain model.