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Prediction of tree biomass in the forest–tundra ecotone using airborne laser scanning

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ABSTRACT

The effect of ongoing climate change on sub-arctic and alpine forests has led to increased interest in monitoring potential changes in the forest–tundra ecotone. In addition to climate change, insect damage, browsing pressure by herbivores such as moose and reindeer, as well as anthropogenic impacts will contribute to changes in the forest–tundra ecotone. These changes are difficult to monitor with manual methods because of the complex mosaic pattern of the ecotone. In this study, the possibility to predict maximum tree height, above ground tree biomass and canopy cover with airborne laser scanning (ALS) was therefore tested at a forest–tundra ecotone site near Abisko in northern Sweden (Lat. N 68°20′, Long. E 19°01′, 420-700 m a.s.l.). The forest in the area is dominated by mountain birch (*Betula pubescens* ssp. *czerepanovii*), which has highly irregular stem and canopy forms. Predictions from two different laser data acquisitions were compared. The first laser data set had 6.1 points m^{-2} and was obtained in 2008 with a TopEye MKII scanner carried by a helicopter flown at 500 m a.g.l. The second laser data set had 1.4 points m^{-2} and was obtained in 2010 with an Optech ALTM Gemini scanner carried by a fixed-wing aircraft flown at 1740 m a.g.l. Linear regression models were developed for the predictions using data from 73 sample plots with ten meter radius surveyed in 2009 and 2010. The relative RMSEs obtained for the TopEye and Optech data after leave-one-out cross-validation were, respectively, 8.8% and 9.5% for maximum tree height; 18.7% and 21.2% for above ground tree biomass; and, 16.8% and 18.7% for vertical canopy cover on plot level. The results were clearly improved by introducing a new procedure to compensate for unevenly distributed laser points. In conclusion, ALS has strong potential as a data source to map mountain birch biomass in the forest–tundra ecotone, even when using sparse point density ALS data.

1. Introduction

The sub-arctic and alpine tree line in northern Scandinavia is most often made up of birch forest dominated by mountain birch (*Betula pubescens* ssp. *czerepanovii*). These forests are characterized by low, often leaning and crooked trees with umbrella-like canopies and slow growth (Fig. 1). The trees have limited commercial value and systematic monitoring of them has not been done in the past (Tømmervik et al., 2009).

There is a growing interest in monitoring this area, especially the tree line, which is expected to change with a warmer climate. Kullman (1998, 2010a,b) predicts that the tree line will advance to higher elevations. However, some studies also indicate that the tree line may retreat (e.g., Crawford et al., 2003). A large change in the tree line would affect animals and plants, as well as existing land uses like reindeer herding and tourism. In addition to climate, the tree line in this area is also influenced by other factors (Van Bogaert, 2010), such as browsing by moose and reindeer, human activities, insect attacks, and possibly bog expansion (Crawford et al., 2003). Of particular significance is the autumnal moth (*Epirrita autumnata*) which defoliates large areas of sub-arctic forests on cyclic intervals of about a decade (Babst et al., 2010; Tenow et al., 2007). These factors, and in particular the local climate, will contribute to an ecotone between birch forest and alpine heath that has a very complex mosaic pattern (Payette et al., 2001). In addition to the tree line changes, an

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Fig. 1. The sub-arctic birch forest in the Abisko area is characterized by low, often leaning and crooked trees with umbrella-like canopies and slow growth.

increase in the biomass of the forest–tundra ecotone can be expected (Hedenås et al., 2011; Tømmervik et al., 2009). Such ecosystem changes over large areas in the north would also influence global carbon budgets (Sjögersten & Wookey, 2009; Tømmervik et al., 2009).

Several definitions of tree line exist (Van Bogaert, 2010) which make comparisons between different studies problematic. Furthermore, the scattered patches of trees make it difficult to use ground based inventories to define a line separating areas with trees from alpine heath. A more convenient approach is to use complete predictions of areas based on remote sensing data. Mapping the tree line using manual interpretation of aerial photos is impractical and dependent on the interpreter (Heiskanen et al., 2008). Medium resolution optical satellite data (e.g., SPOT, Landsat) could be used for large area overviews but will not provide a detailed assessment of the structure, biomass and height of the forest–tundra ecotone (Heiskanen, 2006a,b; Hill et al., 2007; Ranson et al., 2004; Weiss & Walsh, 2009; Zhang et al., 2009). Laser scanning provides the possibility to efficiently retrieve 3D data of the forest, including height and canopy cover, which are the two parameters used in the FAO definition of forest (FAO, 2004). So far only a few other laser scanning studies have been done for the forest–tundra ecotone. Ørka et al. (2012) successfully integrated strip samples of LiDAR with Landsat imagery to delineate the subalpine zone. Næsset (2009), Næsset and Nelson (2007), as well as Rees (2007), showed that scattered trees on the alpine heath above the forest could be detected by laser scanning. Earlier studies have shown that laser scanning works well for predicting forest features in managed boreal forests in Scandinavia when combined with field measurements on sample plots (Næsset et al., 2004).

Until now, laser data have only been available for small areas (often densely scanned), but recently several countries, including Sweden, are being laser scanned with sparse point density, mainly for the purpose of constructing new national digital elevation models. It is therefore of interest to compare biomass predictions from a sparse national laser scanning (about 1 point m^{-2}) to denser alternatives (>5 points m^{-2}).

This study investigated the prediction accuracy of above ground tree biomass, maximum tree height, and canopy cover of mountain birch forest in the forest–tundra ecotone when using models developed from field surveyed sample plot data and corresponding laser data. Results from two different laser data acquisitions with different point densities, flying altitudes and scanner types were compared on sample plot level. The first scanning was performed from a helicopter with 6.1 points m^{-2} and the second from fixed-wing aircraft with 1.4 points m^{-2}. For both laser data acquisitions, the developed models for observed above ground tree biomass were applied to 10×10 m grid cells over the whole area.

2. Materials and methods

2.1. Study area

The study area is about 1 km^2 and located 6 km southeast of Abisko in northern Sweden, centered on Lat. N 68°20′, Long. E 19°01′ (Fig. 2), with elevations from 420 to 700 m a.s.l. The area is characterized by a mosaic pattern of forest and alpine heath vegetation. The vegetation is predominantly mountain birch (*Betula pubescens* ssp. *czerepanovii*), but Juniper (*Juniperus communis*), Rowan (*Sorbus aucuparia*), and Willow (*Salix* spp.) taller than 2 m are also present. The birches in the study area are of the multi-stem type with several stems often sharing the same root system (polymorphism).

2.2. Laser data acquisitions

Laser data were acquired under leaf-on conditions at two occasions with different laser scanners (Table 1). The first scanning was done on August 1, 2008 with a TopEye MkII (denoted TopEye) mounted on a helicopter, and the second scanning was done on August 20, 2010 with an Optech ALTM Gemini (denoted Optech), mounted within a fixed-wing aircraft. In both cases, scanning was performed with the flying direction orthogonal to the main slope.

2.3. Field data

The field inventory was carried out over four weeks in August 2009 (88 sample plots) and two weeks in June 2010 (16 sample plots), occurring between the two laser data acquisitions. A total of 104 sample plots were placed systematically in a grid with 100 m spacing, covering a 1.3×1.3 km area in the forest–tundra ecotone, and each plot center was permanently marked. The grid was aligned orthogonal to the main slope direction with a randomly selected starting point. The aim was to represent the whole transition zone between closed forest and heath, thus 31 of the sample plots had no trees taller than 2 m. Table 2 gives a summary of the 73 forested sample plots used in this study. No trees were found to be recently broken in 2009, but in 2010 four trees were found broken on the sample plots that were field inventoried in 2009. These trees were therefore removed from the field data used with the Optech laser data.

Navigation to the sample plots was made with a handheld GPS. In order to avoid subjective selection of sample plot centers, GPS navigation was terminated when 10 m remained to the sample plot center and a measuring tape was used to navigate the last 10 m. The center position of the sample plot was then measured with sub-dm accuracy using a Real Time Kinematic (RTK) GPS (Trimble R7) with the base station placed 6 km away at the Abisko Scientific Research Station.

The sample plots had a radius of 10 m and the distance to the plot border was measured with an ultrasonic positioning system (UPS; Lämås, 2010). The UPS could be used either with one or three ultrasonic senders. One sender was sufficient to measure distance. To measure a coordinate inside the sample plot, three senders were placed in a triangle, 2 m apart, on a tripod in the center of the sample plot. The receiver's position could then be calculated in two dimensions.

In the field, all distances were measured parallel to the ground because this was most convenient given the hilly terrain. To achieve the correct horizontal area, a correction factor was calculated and applied for each sample plot when processing the field data. For each sample plot a plane was fitted to ground-classified laser points from the TopEye data using the least squares method. The area of a sample plot was then calculated as the horizontal projection of the fitted plane. This projected area was on average 3% and up to 12% smaller than the area of a ten meter radius plot.

When obtaining coordinates for the tree stems, trees with a common root system or overlapping crowns were grouped. For each group, position was measured with UPS and maximum tree height