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Estimation of above- and below-ground biomass across regions of the boreal forest zone using airborne laser

Erik Næsset *, Terje Gobakken

Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, N-1432 Ås, Norway

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ABSTRACT

Regression models relating variables derived from airborne laser scanning (ALS) to above-ground and below-ground biomass were estimated for 1395 sample plots in young and mature coniferous forest located in ten different areas within the boreal forest zone of Norway. The sample plots were measured as part of large-scale operational forest inventories. Four different ALS instruments were used and point density varied from 0.7 to 1.2 m^{-2}. One variable related to canopy height and one related to canopy density were used as independent variables in the regressions. The statistical effects of area and age class were assessed by including dummy variables in the models. Tree species composition was treated as continuous variables. The proportion of explained variability was 88% for above- and 85% for below-ground biomass models. For given combinations of ALS-derived variables, the differences between the areas were up to 32% for above-ground biomass and 38% for below-ground biomass. The proportion of spruce had a significant impact on both the estimated models. The proportion of broadleaves had a significant effect on above-ground biomass only, while the effect of age class was significant only in the below-ground biomass model. Because of local effects on the biomass–ALS data relationships, it is indicated by this study that sample plots distributed over the entire area would be needed when using ALS for regional or national biomass monitoring.

1. Introduction

Forest ecosystems contain the majority of the carbon stored in terrestrial ecosystems (IPCC, 2000). Thus, the world's forests sequester and conserve more carbon than all other terrestrial ecosystems and account for 90% of the annual carbon flux between the atmosphere and the Earth's land surface (Winjum et al., 1993). The carbon is stored both in the form of biomass (trunks, branches, foliage, roots, etc.) and in the form of organic carbon in the soil.

Countries ratifying the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) are committed to report their direct human induced emissions and removals of carbon dioxide in the commitment period 2008–2012 (UNFCCC, 2007). The reporting requirements include emissions and removals of carbon dioxide from Land Use, Land Use Change and Forestry (LULUCF) activities, which comprise deforestation, afforestation, and reforestation activities (Article 3). In addition to national reporting of emissions and removals of carbon dioxide, mechanisms in the Protocol allow countries to implement joint projects aimed at reducing atmospheric carbon dioxide through LULUCF activities, e.g. forest management (Article 4).

Streck and Scholz (2006) claimed that the challenge of monitoring LULUCF projects has led to criticism of such projects. Full carbon accounting, i.e., assessment of carbon fluxes within all compartments of a forest ecosystem, can be achieved by choosing among various scientific models, tier-levels, which have been developed by the Intergovernmental Panel on Climate Change (IPCC) and the Food and Agriculture Organization of the United Nations (FAO) in collaboration with scientific forestry research institutions (Penman et al., 2003). The most appropriate tier level for available data should be used. Applying state-of-the-art remote sensing techniques in combination with terrestrial surveys may be a feasible way to guarantee accurate monitoring of activities and impacts during a project's lifetime (Streck & Scholz, 2006).

LIght Detection And Ranging (LiDAR) is one of the most promising technologies for retrieval of various forest biophysical properties (e.g. Holmgren et al., 2003; Næsset, 2002; Nilsson, 1996; Ritchie et al., 1993) and for characterization of forest canopy elements in three dimensions (e.g. Harding et al., 2001; Lovell et al., 2003) while accurately mapping the terrain below forest canopies (Hodgson & Bresnahan, 2004; Kraus & Pfeifer, 1998; Reutebuch et al., 2003). Thus, airborne LiDAR holds potential for timely and accurate measurement of tree biomass components over time that complies with those requirements of the international conventions that are related to carbon stored in trees.

Airborne LiDAR instruments that are relevant for remote sensing of forests are pulse ranging instruments that record multiple laser returns, or systems that digitize the entire amplitude of the backscattered energy

* Corresponding author. Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway. Tel.: +47 64965734; fax: +47 64968890.
E-mail addresses: erik.naesset@umb.no (E. Næsset), terje.gobakken@umb.no (T. Gobakken).

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(Lim & Treitz, 2004). Airborne LiDAR instruments that distribute laser points along a path following the trajectory of the aircraft are referred to as laser profiling instruments, whereas laser scanning instruments distribute laser points in the along- and across-track directions. Above-ground forest biomass has been estimated using full waveform laser scanning (e.g. Drake et al., 2002a,b, 2003; Lefsky et al., 1999; Means et al., 1999), discrete return laser profiling (e.g. Nelson, 1997; Nelson et al., 1988, 2004, 2007), and discrete return laser scanning (e.g. Hall et al., 2005; Lim et al., 2003a; Næsset, 2004c; Omasa et al., 2003; Stephens et al., 2007; Thomas et al., 2006). A precise estimation of total above-ground biomass relies on a strong relationship between amount of foliage and the various above-ground biomass components since foliage normally is the main element blocking the laser pulses. Attempts have also been made to estimate below-ground biomass from discrete return data (Næsset, 2004c), and results indicated that below-ground biomass can be estimated fairly well with airborne LiDAR because the quantity of below-ground biomass is related to the size of a tree which is highly correlated with the three-dimensional structure of the tree as derived from LiDAR data.

Airborne LiDAR systems with the capability of collecting laser data along a corridor with a width of up to many hundred meters in one overflight are now being used operationally in commercial, area-based forest inventories using the individual stands as the primary units (Næsset, 2004d; Næsset et al., 2004), which means that there is a full "wall-to-wall" coverage of LiDAR data over the entire inventory area. Due to the ability to provide precise information about the timber resources and biomass stocks, airborne laser scanning (ALS) is also considered as a useful tool for regional monitoring purposes (Gobakken et al., 2006; Næsset, 2005b; Stephens et al., 2007), i.e., monitoring of the forest resources at a county or state level, which is the primary unit of the national forest inventory program of many countries. The typical size of such regions could be 5,000–50,000 km^2.

The use of ALS as a regional biomass monitoring tool requires that biomass can be assessed for different forest types and by different instruments because when ALS is used for monitoring purposes it is likely that different instruments will be used over time due to rapid technological development. Previous studies have developed strong site-specific relationships between canopy metrics derived from ALS data and forest biophysical characteristics such as above-ground biomass. However, little is known about the generality of these relationships except for two studies using full waveform and large-footprint ALS (>10 m diameter) (Lefsky et al., 2002, 2005). Lefsky et al. (2002) were successful at developing a unified equation for predicting biomass in multiple biomes and Lefsky et al. (2005) reported robust biomass equations across five diverse sites in the Pacific Northwest.

Much of the research related to ALS and biomass estimation has been conducted in temperate forests and in ecosystems with dominance of deciduous tree species. It has been shown that for such ecosystems total above-ground biomass can be estimated with good results and e.g. Lefsky et al. (1999) and Drake et al. (2002a) reported a coefficient of determination between forest biomass and ALS-derived variables in the range between 0.8 and 0.93. Except for a few studies related to forests with high biomass (e.g. Drake et al., 2002a, 2003) or using profiling systems (e.g. Nelson et al., 1997, 2003), the biomass studies have been limited to certain very local test sites. Published studies from coniferous forests of the boreal forest zone are few in numbers and they are also limited to a few local sites with limited spatial extension.

As there is an increased interest in carbon accounting in forest ecosystems, there is a need for efficient methods to estimate the various tree biomass components across large regions. The objective of the present study was to assess the feasibility of ALS to estimate above- as well as the below-ground biomass in boreal forest types found at 10 sites spread across the southern part of Norway using small-footprint data from different ALS instrument with a moderate sampling density of ~1 pulse per meter square. Furthermore, it was assessed whether estimated ALS–biomass models differ between forest types and geographical regions. Finally, the influence of laser instrument on the estimated relationships was evaluated.

2. Materials and methods

2.1. Study areas

This study was based on data from 10 different forest areas in south Norway (Fig. 1, Table 1), and these were the first areas inventoried by means of ALS for forest management purposes. The sample plots used in the present study had been measured as part of these operational stand-based forest inventories, where the sample plot data were used to estimate equations that related ALS-derived variables to biophysical properties of interest. The size of the inventories varied from approximately 10 to 960 km^2 and the altitude varied from 40 to 900 m a.s.l. All these 10 areas were located within a geographical region of approximately 90 km × 390 km. The Scandinavian mountain chain divides south Norway into two distinct parts along a SW–NE axis, with strong oceanic influence on the climate on the western side (area 5) with mild winters and high annual precipitation, some oceanic influence along the coast in the southern part (like areas 1 and 4), and typical continental climate in the inland with dry climate and cold winters (areas 3 and 10). Thus, the 10 areas spanned much of the natural variation found in the boreal forest of the Nordic region. The main tree species were Norway spruce [*Picea abies* (L.) Karst.] and Scots pine (*Pinus sylvestris* L.). Further details about areas 1–3 in particular can be found in Næsset (2002, 2004a,d).

2.2. Field data

The field data for the 10 areas were collected from 1998 to 2006. In total, 1395 circular sample plots with size 200–400 m^2 were distributed systematically throughout the study areas according to regular grids. The plots were classified according to tree species composition (proportions of spruce, pine, and broadleaves), age class, and site index by photo interpretation using stereo photogrammetry. The H_{40}

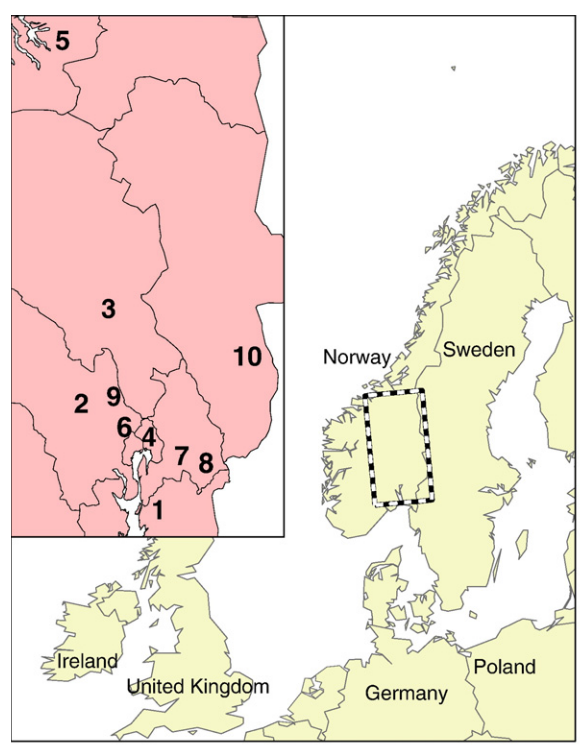

Fig. 1. Map of the locations for areas 1, 2, …, 10.