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Can airborne laser scanning assist in mapping and monitoring natural forests?

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ABSTRACT

Old-growth boreal forests display high within-stand structural variation, with large variation in tree sizes and age structure, a heterogeneous horizontal spatial pattern with gaps of different sizes and multi-layered canopies. Old managed forests, on the other hand, are characterized by more homogeneous structural patterns. In many parts of Europe, no true 'virgin forests' remains. Still, in many places forests previously influenced by selective logging have been abandoned, and is now developing towards a more natural forest structure. Such near-natural forest areas can be of special importance for forest biodiversity and related ecosystem services, and it is therefore important to map and monitor such forests. Recently, airborne laser scanning (ALS) has been applied to provide ecologically relevant information on forest structure. The advantage of ALS is that it can characterize three-dimensional forest structure in fine detail across broad areas, replacing more labour-intensive field-based measurements.

In this study, we use ALS to compare the structural characteristics of 89 near-natural and 280 managed old forest stands in a 17,000 ha boreal forest study site in southeastern Norway. For the study area, both maps of logging history separating old near-natural and old managed forests, and high-resolution ALS data was available.

Our aim was to investigate if ALS data could be used to separate vertical and horizontal forest structure in old near natural versus old managed forests. We also wanted to compare different methods for classification, and to describe the potential for use of ALS in classification of forest naturalness for future mapping and monitoring purposes.

We found that ALS data had a strong potential in separating stands of old near-natural forests from old managed stands. The most important metrics for classification were those reflecting canopy height, canopy density, variation in canopy height, number of trees per area and gap patterns. This fits well with ecological knowledge of relevant structural differences between forests of different degree of naturalness. Both vertical and horizontal metrics provided useful input to the classification, but the horizontal metrics performed slightly better on accuracy and were easier to interpret. Although the method has a good potential for wider use in boreal forest landscapes, the need for local reference data for calibration as well as the importance of ALS pulse density for precision of classification should be further investigated.

Large-scale spatial information on remaining source areas of natural and near-natural forests will be essential in order to manage forests in a way that safeguards biodiversity and ecosystem services. We suggest that classification of forest naturalness based on ALS data can be a helpful tool in future forest mapping and monitoring.

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1. Introduction

Forest management changes structures and affects biodiversity in forest habitats. While old-growth boreal forests display high within-stand variation in age and size of trees as well as large amounts and diversity of dead wood and old trees, managed boreal forests display a more homogeneous tree composition, age structure and vertical stratification (Siitonen, 2001). Several species groups are negatively affected by forest management and the effect increases with intensity (Paillet et al., 2010; Ulyshen, 2011; Nordén et al., 2013). Recent studies also point to the importance of a large-scale perspective on forest biodiversity management (Kouki et al., 2012; Nordén et al., 2013). Therefore, development of methods for large-scale mapping of forest characteristics related to low-impact management and high degree of naturalness is increasingly urgent.

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In Northern Europe, only very small amounts of true old-growth forest remain today (in Norway estimated as 1.3% of the total forest area (Tomter and Dalen, 2014, p. 113)). Logging, initially extensive but increasing in intensity and extent over the centuries, gradually changed the Fennoscandian forest landscape from the 15th century and onwards (Siitonen, 2001). By the end of the 19th century, the forest in Norway and southern parts of Sweden and Finland was a landscape of varying but widespread forest management influence. Selective dimension felling was the common harvesting regime. Even though the standing timber volume was much reduced by dimension cutting (Esseen et al., 1997; Siitonen, 2001), recent studies emphasize that the selectively logged forests could still be structurally heterogeneous with a diverse age- and diameter-distribution (Lie et al., 2012). According to Lie et al. (2012), this varied forest structure "most certainly enabled many forest-dwelling species to persist during the early phase following the felling".

From the mid-twentieth century, clear-cutting and planting replaced the selective logging regime in Fennoscandia. Today, the majority of the forest area has been cut by modern stand-replacing methods (e.g. ~75% of Norwegian productive forest; Storaunet and Rolstad, 2015). At the same time, the first clear-cut stands, dating from the period after the Second World War, are starting to reach maturity. These old managed forests are even-aged and more homogeneous, with low densities of structural legacies (old trees, coarse dead wood etc.) important for several red-listed forest-dwelling species (Lindenmayer et al., 2006; Kuuluvainen, 2009). In this paper, we refer to such forest as *managed forests*.

As the old, selectively logged forests (in this paper denoted *near-natural forests*) are successively being cut by stand-replacing logging, the remaining area of forests only influenced by selective logging is rapidly diminishing in Fennoscandia (Siitonen, 2001; Vennesland et al., 2006; Magnusson et al., 2014; Storaunet and Rolstad, 2015). This remaining selectively logged forests now left without human intervention for a hundred years or more, are continuously developing towards the structural characteristics of a natural forest (Jönsson et al., 2009). Studies show that certain old-growth characteristics like age distribution and late-decay dead wood can be obtained approximately 100 years after selective logging, depending on the site productivity and the previous logging intensity (Storaunet et al., 2000, 2005; Jönsson et al., 2009). Studies from lowland woodlands in continental Europe show that secondary old growth may provide important new strongholds for recovery and recolonisation of an important share of old-growth related species (Vandekerkhove et al., 2011).

This indicates that the remaining old near-natural forests – affected only by selective dimension felling in the early twentieth century – can increasingly function as substitutes for true old-growth forests, offering structural characteristics that can provide habitat for a range of specialized species, including many red-listed species. It is therefore paramount to establish efficient methods for identifying, delineating and monitoring the remaining areas of such forests, which may represent a baseline for future conservation policies.

During the last two decades, methods for mapping forests with airborne laser scanning (ALS) have emerged. Today, ALS is a standard tool for providing stand-level forest inventories for management purposes over large areas in the Fennoscandia (Næsset, 2007, 2014; Maltamo and Packalen, 2014) as well as in many other countries around the world (Maltamo et al., 2014b). The high spatial detail, the potentially large area coverage and the increasing availability of such data make them an attractive source for mapping and monitoring of forest habitats. Furthermore, the detailed three-dimensional structural metrics that can be derived from ALS data provide information useful for classifying successional stages of forests (Falkowski et al., 2009). ALS is also increasingly being used in ecological studies in forests, both for biodiversity assessments and single-species studies (Hill and Thomson, 2005; Pirotti et al., 2012; Maltamo et al., 2014b; Müller and Vierling, 2014).

The aim of the current study was to evaluate the potential of ALS data to capture structural differences between old near-natural forests and old managed forests that can be used to separate these two types of old forests. We expected information inherent in ALS data to capture structural differences between old near-natural forest and old forest created by stand-replacing harvest related to both vertical and horizontal structure. In the vertical dimension, we expected near-natural forests to have more variation in tree height and spatial arrangement of tree crowns. In the horizontal dimension, we expected a less uniform spatial distribution of trees, reflected by several metrics taking into account the information in the spatial distribution of the planimetric coordinates of the individual ALS recordings. We also expected different gap patterns, with more gap area and more variation in gap size in the old near-natural forest. Similar horizontal metrics derived from high-resolution satellite imagery have earlier shown potential for discriminating between forest age classes (Nelson et al., 2002, 2004). A few earlier studies have used ALS in attempts to separate forests of different degree of naturalness (Bater et al., 2009; Vehmas et al., 2011), but to the best of our knowledge this is the first study to include specific horizontal metrics in such classification.

Here, we study an area containing a mixture of old near-natural forests and old managed forests for which we have access to old maps indicating previous logging history, as well as recent high-resolution ALS data. We ask the following questions:

(1) Can ALS data be used to separate vertical and horizontal forest structure in old near-natural forests versus old managed forests, and if so, which structural metrics can be used for such classification and what are their ecological relevance?
(2) Which classification method (logistic regression, random forest algorithm or boosted regression trees) should be used in order to maximize the accuracy when identifying old near-natural forests from ALS data?
(3) How can the methods be adapted for use in other forest areas?

2. Materials and methods

2.1. Study area

The study area was located within a 17,000 ha forest property in the boreal zone in southeastern Norway, approximately 100 km north of Oslo (N60° 23′, E10° 55′) (Fig. 1). The altitude of the study sites was between 400 and 760 m above sea level. Norway spruce (*Picea abies*) is the dominant tree species in the area and the vegetation was either mesic and *Vaccinium*-dominated or more moist vegetation types that were dominated by ferns. The study area is privately owned and the property has a well-documented history of extensive logging throughout the 20th century. Information on local forest age and the likely application of selective cutting was recorded as early as 1906, but mapping of stand age and stand conditions were not completed for the entire area until 1954. After this, all management operations were recorded in all stands (average stand size ~5 ha) and an inventory of forest age and stand conditions was repeated every 10 years.

We combined current digital forest maps with scanned and georeferenced historical forest maps from 1954 and 1964 to obtain reference data. We considered only forest stands categorized as old

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