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Effects of auxiliary data source and inventory unit size on the efficiency of sample-based coarse woody debris inventory

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ABSTRACT

The efficiency of a sample-based inventory can be greatly improved if lower cost information on the study area is utilized. It has been observed that the use of airborne laser scanning (ALS) data in the design phase may improve the efficiency of dead wood (coarse woody debris, CWD) volume inventory notably, i.e. a smaller standard error of the mean is observed with the same inventory costs. In the present case, several auxiliary data sources were employed in the design phase by using 'probability proportional to size' sampling to select the sample units to be inventoried in the field. It was observed that a combination of ALS data with either aerial photographs or stand-register data can improve the sampling efficiency even more than the use of ALS as a single data source. Since these additional data sources are often gathered for the inventory of living trees, their use does not incur extra expenses for CWD assessment. Thus, the use of these data separately or together with ALS data can greatly improve the cost-efficiency of a CWD volume inventory. It was also observed that the size of the sample units has a slight effect on the sampling efficiency. Even though the improvement in the sampling efficiency was usually greater with larger sample unit sizes, the CWD volume inventory was most efficient with moderate grid cell sizes.

Introduction

Intensive forest management, prevention of forest fires, the cutting of firewood and the removal of damaged trees due to the fear of insect pests have reduced the numbers of dying and dead trees in managed forests to a small proportion of those in natural, unmanaged forests. Thus, dead wood (coarse woody debris, CWD) volumes in Fennoscandian managed forests have decreased to less than 10% of those in old-growth forests (Siitonen, 2001). Since dying and dead trees provide habitats for thousands of threatened animal, plant and fungal species, and as CWD is regarded as one of the main biodiversity indicators, it is of special importance to assess the amount and distribution of CWD when considering the biodiversity aspects in forest management (Samuelsson et al., 1994). Also, the type, size, tree species, decay class and continuity of the dead wood are important aspects to be taken into consideration besides the total CWD amount when assessing the quality of habitats for various saproxylic (i.e. dead wood dependent) species (see Siitonen, 2001; Dahlberg and Stokland, 2004). Knowledge of the incidence and location of biodiversity indicators is needed for the optimal focusing of conservation efforts and monitoring of the quality of managed forests for saproxylic species, for example.

Since accurate information on forest resources is needed for forest management planning and decision-making, new possibilities have been explored for improving the cost-efficiency of forest inventories. More efficient field inventory methods and sampling strategies have been developed and tested, but it is largely the use of remote sensing methods that has markedly reduced inventory costs for large areas. There is a long tradition of using satellite images and aerial photographs in forest inventories (e.g. Standish, 1945; De Steiguer, 1978), and nowadays airborne laser scanning (ALS) is regarded as one of the most promising remote sensing methods, since it provides direct measurements of the physical dimensions of the Earth's surface and vegetation. This means that its usability is not limited by the illumination conditions, for example (Næsset, 2004). ALS can measure both intensity (strength of the return signal) and height information, and multiple returns can be recorded for each pulse emitted (Wehr and Lohr, 1999). One pulse can generate multiple returns if it encounters an object through which it can penetrate at least in part. Usually it is only the first and last return pulses that are utilized, however.

Concerning biodiversity, aerial photographs have been used, to identify standing dead trees, for instance (Haara and Nevalainen, 2002), and to assess damage caused by drought or other phenomena (Holopainen et al., 2006; Meentemeyer et al., 2008). Various ALS metrics represent the vegetation structure, and those

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can be used to predict the characteristics of the growing stock (e.g. Næsset, 2004, 2007). Since it has been observed that CWD volume is highly correlated with living tree characteristics (Siitonen, 2001), the use of existing stand-register data (see Chojnacky and Heath, 2002) and ALS for CWD inventories has been studied (e.g. Pesonen et al., 2008a,b). Both Kim et al. (2009) and Bater et al. (2009) used ALS data to assess standing dead trees in the USA. Kim et al. (2009) used ALS derived intensities to estimate standing dead wood biomass, and Bater et al. (2009) estimated the wildlife tree class distribution of standing dead trees. In Finland, ALS data have been successfully used to estimate downed and standing dead wood volumes in a conservation area (Pesonen et al., 2008a). The CWD dynamics in managed forests are quite different, however, and the direct use of ALS data for CWD volume prediction in these cases has proved challenging. Thus, ALS data have mainly been used as auxiliary information in CWD inventories in managed forests (Pesonen et al., 2008b).

Auxiliary information can be used to improve the cost-efficiency of sample-based forest inventories, i.e. to reduce the standard error of the mean given the same inventory costs, whenever there are some auxiliary variables which correlate with the variable of interest, they are inexpensive and easy to measure, and their values are known for each population element in the area (De Vries, 1986). Remote sensing data for large areas can be obtained nowadays at low costs, so that this is the most obvious source of auxiliary information for forest inventory purposes.

Auxiliary information can be used in either the design or estimation phase or both (see Thompson, 2002; Lehtonen and Pahkinen, 2004). In the design phase, it can be utilized before the field inventory as a basis for pre-stratification or in unequal probability sampling, for example (see Särndal et al., 1992; Tuominen et al., 2006). The latter in which the selection probability of each sample unit depends on its auxiliary data value (size measure) is referred to as probability proportional to size (PPS) sampling. This technique enables the sampling effort to be concentrated in areas where there is a higher probability of finding the variable of interest. If the correlation between the variable of interest and the auxiliary variable is highly positive, the estimates for the population total become close to constant among the population units, and therefore the sample variance in PPS sampling is small (see Särndal et al., 1992). Negative correlation leads to inefficient sampling, however, and therefore some transformation to an auxiliary variable or regression model needs be used to render the correlation positive. In the estimation phase, auxiliary information can be used for a given sample in order to improve the accuracy of the estimates by using ratio or regression estimators or post-stratification, for example (see Thompson, 2002; Lehtonen and Pahkinen, 2004).

The purpose of the present work was to improve the efficiency of sample-based CWD inventory by using auxiliary variables which describe the characteristics of living trees. The auxiliary information was derived from ALS, aerial photographs or existing stand-register data and was used in the design phase in guiding the field inventory of CWD by means of PPS sampling. The use of auxiliary information produced by combining ALS data with aerial photographs or stand-register data were also tested, as was the effect of sample unit size on the sampling efficiency. Downed (DDW) and standing dead wood (SDW) were studied separately in addition to the total CWD volume (standing and downed dead trees combined).

Material

The study area and data collection

The field data were collected from commercially managed forests in the Sonkajärvi district in central Finland in the summer of 2007, by measuring 33 randomly located 100 m wide strips which varied in length from 188 to 2824 m and were oriented in a north-south direction. Only 25 of these 33 strips are considered here, those for which ALS data, updated stand-register data and aerial photographs acquired at about the same time were available. The total area of these 25 field inventory strips was approximately 250 ha.

All the standing dead trees (and snags) which had a mid-point located inside the strip and downed dead trees (and logs) which had their stump or large-end inside the strip were measured. The large-end (stump-height) diameter was required to be greater than 10 cm, and only pieces of CWD longer than 0.5 m were measured. The characteristics recorded for the standing and downed dead trees were diameter at breast height, or at the mid-point, and total height or length. The diameter at the mid-point was measured instead of breast height if the pieces were shorter than 1.3 m or the breast height could not be ascertained. Huber's formula was used to calculate the volumes for those trees which had their diameter measured at the mid-point (see Schreuder et al., 1993), and the volume functions or taper curves of Laasasenaho (1982) were used for those trees which had their diameter measured at breast height. If piles of trees left from commercial thinnings or other human activities were found, the volumes of timber involved were estimated from the pile dimensions or the dimensions of single trees. All the observations were positioned by Global Positioning System (GPS) and differentially corrected using a base station located in the same municipality.

For the sampling simulations, the area covered by the 25 field inventoried strips was divided into square grid cells (sample units) of four sizes: 10 m × 10 m (giving a total of 25,030 grid cells), 20 m × 20 m (6230 grid cells), 25 m × 25 m (3976 grid cells) or 50 m × 50 m (980 grid cells). One-fourth of the grid cells were taken in each case to form the modelling data sets, and the remaining three-fourths formed the simulation data sets used to test the efficiency of the CWD inventory with different auxiliary data sources. The modelling cells were distributed uniformly over the area and were selected systematically. The ranges and averages of the CWD volumes for the whole area and the two partial data sets are presented for the various grid cell sizes in Table 1.

Laser data

The georeferenced ALS point data from Sonkajärvi were collected on 27 and 28 July 2006 using an Optech ALTM 3100 scanner operating at a mean altitude of 2500 m a.g.l. (above ground level), which resulted in a nominal sampling density of about 0.5 measurements m^{-2} when a pulse frequency of 50 kHz was used. The data were captured using a half-angle of 15°, resulting in a swath width of 1350 m.

The Optech ALTM 3100 laser scanner captures from one to four range measurements for each pulse (see, e.g. Stilla and Jutzi, 2008). Only the echo categories 'last of many' and 'only' were used for constructing the digital terrain model (DTM). The laser points were classified as ground and non-ground hits using the TerraScan software and the method explained in Axelsson (2000). A pixel size of 1 m was then used to create a raster DTM by calculating for each pixel the mean height of the ground points which were located inside that cell. Values for the raster cells which did not include ground points were derived using Delaunay triangulation and bilinear interpolation.

The existence of large rocks, shrubs, branches or pieces of CWD, for example, may have some effect on the construction of the DTM, since the determination of the ground level may be especially problematic in rocky terrain or in cases where there are large piles of downed dead wood. Small branches and shrubs have been noted to have only a slight effect on the altimeter observation, however