Integrating field and lidar data to monitor Alaska’s boreal forests

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Introduction

Inventory and monitoring of forests is needed to supply reliable information on forest resources both nationally and internationally. According to the global Forest Resources Assessment for 2005, the United States is among the relatively few countries in the world with recent high-quality information on change in forest area and biomass (FAO 2006). While true for much of the U.S., this is not the case for all of the country. The boreal forests of interior Alaska, which are believed to comprise 14-15% of U.S. forest land area, are not currently included in the National Forest Inventory (NFI) of the U.S. and have never had a comprehensive forest inventory. As with many forests in developing countries, attributes for the roughly 45 million hectares of boreal forests in Alaska are a combination of expert opinion, outdated inventories from limited portions of the more accessible land, and information from very low resolution (1 km) remote sensing data (Van Hees in press).

The Forest Inventory and Analysis (FIA) program, which is responsible for the NFI of the United States, has proposed including Alaska in the NFI but has also recognized that the inventory system may need to be modified from that used in the rest of the country (USDA Forest Service 2007). Low road density and lack of infrastructure make field plots expensive compared to other U.S. states, as most forest locations can only be accessed with helicopters. Heavy and persistent cloud cover, variable topography, limited coverage of GPS base stations, lower market demand for aerial photography, and optimization of NASA’s remote sensing platforms for temperate latitudes all contribute to the difficulties of using remote sensing information. At the same time, there are also potential gains in efficiency through the combined use of high resolution airborne remotely-sensed data and field data. In particular, airborne laser scanning (lidar) has shown potential for characterization of boreal forests (Andersen 2009).

The perceived need for a monitoring program in the boreal forests has changed dramatically in recent years, primarily due to increased concern over climate-related impacts. Climate impacts are very difficult to predict, not just because of the uncertainty of the climate but also because of the complexity of the boreal ecosystem and the many feedback loops among components. For instance, longer or drier summers may increase fire frequency, and fires can remove insulating organic material and blacken the soil, which can in turn melt underlying permafrost; melting permafrost can cause thermokarst, where previously forested areas collapse below the water table, which in turn impacts fire danger. Depending on relative strength of the multiple interactions, magnitudes and direction of change can alter, making early monitoring critical to understanding the future for boreal forests. In this extended abstract, we present a method to optimize the efficiency of an inventory design using a combination of field plots and lidar data to provide estimates for some key indicators for monitoring climate-related changes.

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Methods

To gain greater understanding of monitoring needs in the boreal forest, the Forest Inventory and Analysis program held client meetings in Anchorage, Alaska in 2006 and 2008. Researchers and land managers from Alaska participated in discussions and presentations about expected changes in boreal forests and impacts on forest uses. Combining information from these meetings with a literature review and the development of simple conceptual models, we identified a number of key forest indicators where future conditions are uncertain and monitoring could provide early information on direction and magnitude of trends. We report here for four of these indicators: (1) forest area (km²); (2) total carbon in above-ground tree biomass (metric tons); (3) hardwood forest area (km²); and (4) presence of invasive species (km²). While this is only a selection of the important indicators for monitoring change in boreal forests, the selection spans the range of correlation between field and lidar data, providing a good understanding of tradeoffs among varying designs in achieving precise estimates of different indicators.

To be able to provide consistent national estimates of both real-valued and classified attributes, we assumed that the basic plot layout, definitions, and core measurements would be the same in Alaska as for the rest of the U.S. While most of the country collects some forest health attributes on a 1/16 subsample of plots, we would use standardized simplified protocols on all plots for understory vegetation, downed woody material, and soils. In addition, the proposed Alaska protocol would collect a depth to frozen ground measurement, important to modeling permafrost, and some basic information on mosses. We tested all of the proposed protocols with field trials using crews of two or three people, and used a process of testing and revision to create a set of field measurements that could be consistently completed within 1 day by a three-person crew.

An annualized inventory system, which would measure a panel of field plots from throughout Alaska each year, was dropped from consideration due to logistical and cost constraints. Instead, the proposed inventory would use five inventory units in the boreal region (fig. 1), each assessed within a time span of two to three years, with a 10 to 12 year interval between remeasurements. We tested the efficiency of various combinations of a double-sampling design with lidar and field data in the Tanana inventory unit (fig. 1) using two strata: the Legacy Stratum contained all the land included in a 1970s timber inventory, and the New Stratum contained more nonforest and black spruce but a very small expected proportion of white spruce and hardwoods. Any point within each stratum would have an equal probability of selection.

Ideally, a preliminary sample would be used to estimate population variability of the four chosen indicators. Lacking resources to do this, we instead used available information to construct expected population variability. From recent inventories in south-central Alaska that used the identical plot layout, 340 field plots that contained boreal forest types (white spruce, black spruce, aspen, paper birch, cottonwood, and balsam poplar) were identified. We developed an expected proportion of forest in the Tanana inventory unit, using the NLCD 2001 classification of LandSat Thematic layers (Homer et al. 2007). A 1971-74 air photo classification provided data for estimating proportions of forest types in the Tanana inventory unit. The 340 field plots were reweighted by the expected probability of different forest types, and bootstrapped with 1000 repetitions to make an estimate of expected population variability for each of the four indicators for each stratum. Stratified sampling was used to estimate precision with varying numbers of field plots and double-sampling for regression was used to estimate precision with varying...
numbers of field plots and lidar plots (Cochran 1977). Correlations between lidar measurements and field measurements for each objective were developed using a data set of lidar and field data from the Kenai peninsula and assumed to be similar for the Tanana region: 0.70 for carbon; 0.60 or forest area, 0.50 for hardwood forest area, and no correlation for presence of invasives. Costs for the field portion of the inventory included training, equipment, transportation, salary,

![Figure 1. Proposed inventory units for Alaska and approximate extent of forest area.](image)

...and overhead, for an average plot cost of US$7022 in the Legacy Stratum and US$8282 in the New Stratum. Costs for lidar were assumed to be US$500 per plot based on other similar recent lidar acquisitions in the region, with lidar point density at 0.5 meters.

**Results**

The sampling errors for the NFI default design of one field plot per 2400 ha are shown in Table 1. The NFI default design would cost about US$0.55 per forested ha per year for the boreal forests of Alaska, or $25 million per year. With budget constrained to a more realistic level of $0.10 ha⁻¹yr⁻¹, optimal field / lidar combinations would result in higher sampling error than the NFI default level, but would improve sampling errors for Carbon, Forest Area, and Hardwood Forest Area compared to optimized field plots alone (Table 1). The decrease in the efficiency ratio of sampling error to cost as budgets are constrained is the result of the nonlinear relationship between numbers of plots and sampling error (Figure 2).
Table 1. Estimates and sampling errors (SE) of four indicators for the Tanana inventory unit.

<table>
<thead>
<tr>
<th></th>
<th>Carbon</th>
<th>Forest area</th>
<th>Invasives</th>
<th>Hardwood forest area</th>
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<tr>
<td></td>
<td>megatonnes</td>
<td>km²</td>
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<td>1198.5</td>
<td>15791.8</td>
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<td>3.32</td>
<td>808.0</td>
<td>163.2</td>
<td>532.2</td>
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<td></td>
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<td>of 1 plot per 2400 ha</td>
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<tr>
<td>SE - field only,</td>
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<td>1483.2</td>
<td>293.1</td>
<td>944.7</td>
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<td>optimized at US$0.10 ha⁻¹yr⁻¹</td>
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<tr>
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<td>at US$0.10 ha⁻¹yr⁻¹</td>
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The optimal sampling intensities for the 0.10ha⁻¹yr⁻¹ budget were a 5:1 ratio of lidar plots to field plots for Carbon and Hardwood Area indicators in both strata, a 6:1 ratio of lidar plots to field plots for the Forest Area indicator, and no use of lidar for the Invasives indicator. These optimal solutions for the Carbon and Hardwood Area indicators result in a sampling intensity of field plots of 1 plot per 9,098 ha in the New Stratum and 1 plot per 13,646 ha in the Legacy stratum. For the Forest Area indicator, these intensities would be reversed. For the Invasives indicator, optimal intensities at the $0.10 budget constraint are one plot per 9600 ha in the New Stratum and one plot per 7200 ha in the Legacy stratum.

Figure 2. Precision of indicators as a percent of the estimate by sampling intensity

To understand the potential cost savings of using double sampling with a lidar/field plot combination compared to field plots alone, we solved an additional set of problems where precision for each indicator was constrained to that achievable with a budget of $0.10ha⁻¹yr⁻¹ using field plots alone, and the objective was set to minimizing cost. Using field plots alone, the cost would be $4.15 million per year. The same level of precision for carbon estimates could be achieved by combining lidar and field data with a savings of $1.22 million per year; equivalent
savings when the primary objective was monitoring area of forests would be $1.00 million per year. For an objective of monitoring hardwood forest area, savings would be $0.50 million per year. No savings would be possible for the objective of monitoring invasives.

**Discussion**
A great deal of work remains to be done in finding optimal sample survey and statistical estimation methods of incorporating remote sensing data with field data for monitoring forests. While we used double sampling for regression to combine lidar and field data, due to easy adaptation to a variety of objectives and compatibility with existing NFI database structures and data delivery systems, other researchers have suggested model-based or model-assisted methods would work well for indicators such as volume or carbon. However, even with our simple double-sampling approach, the benefits of incorporating lidar were clear. For a fixed forest inventory cost of US$0.10 per forested ha, the reduction in uncertainty of a 95% confidence interval for carbon in forests in the Tanana inventory unit realized by incorporating lidar into the standard inventory would be 4.1 million metric tons, which is about 32 percent of the state of Alaska’s annual carbon emissions from all commercial, industrial, residential, transportation, and electric power sources. While the lidar does not increase efficiency for all indicators, the gains in efficiency for several important indicators make the tradeoff of shifting a portion of the field budget to remote sensing acquisition a robust solution overall.

**Conclusion**
Supplementing NFI field plots with lidar data would be economically efficient for monitoring some, but not all, indicators for climate change impacts on boreal forests in Alaska. These results are the consequence of the very high-cost of field data, and may not hold true for other regions. Further work on improved sampling designs, such as including areal complete satellite information, would be helpful, as would refinement of lidar models for specific indicators.

**Literature Cited**


