Airborne Laser Scanning Based Timber Volume Estimation Using National Forest Inventory and Forest Management Inventory Data – a Comparison

Johannes Rahlf  Marius Hauglin  Rasmus Astrup
Johannes Breidenbach
Division of Forest and Forest Resources, Norwegian Institute of Bioeconomy Research (NIBIO)

October 26, 2020

Abstract

Large-scale forest resource maps based on national forest inventory (NFI) data and airborne laser scanning (ALS) may facilitate synergies between NFIs and forest management inventories (FMIs). Traditionally, FMIs and NFIs have been completely separate activities. Increasing availability of detailed NFI-based forest resource maps provide the possibility to eliminate or reduce the need of field sample plot measurements in FMIs if their accuracy is similar. We aim to 1) compare the performance of a model used in a NFI-based map and models used in a FMI at plot and stand level, and 2) evaluate utilizing additional local sample plots in the model of the NFI-based map. Predictions and estimates based on models of an existing NFI-based map and an FMI were compared at plot and stand level. The improvement of the NFI-based map by adding local sample plots to NFI data was analyzed. Predictions of the NFI-based map were similarly accurate when using training data of the respectively other model for validation. When compared to independent forest inventory data, the NFI model was more accurate than the FMI. The addition of local plots did not clearly improve the NFI model. The comparison indicates that NFI-based maps can directly be used in FMIs for timber volume estimation in mature spruce stands, leading to potentially large cost savings.

*Email: johannes.rahlf@nibio.no
1 Introduction

Forest management inventories (FMIs) in the Nordic countries (Næsset et al., 2004) mainly provide stand-level information in order to support forest management decisions, while national forest inventories (NFIs) mainly provide statistics for reporting and policy making on regional to national scale (Tomppo et al., 2010). Traditionally, FMIs and NFIs have been completely separate activities but the increasing availability of fine-resolution remotely-sensed 3D-data such as large-scale or even nationwide airborne laser scanning (ALS) campaigns have triggered the creation of detailed national forest resource maps, and as a consequence, the search for synergies between NFIs and FMIs (Kangas et al., 2018a).

Fine-resolution 3D data has been used in forest inventories for many years. Remotely sensed data from ALS or digital aerial photogrammetry (DAP) allow accurate estimation of forest stand parameters (Rahlf et al., 2014) to support forest management decisions (Kangas et al., 2018b). In the Nordic countries, ALS is currently the most common method for the acquisition of auxiliary data in FMIs (Næsset, 2014; Maltamo and Packalen, 2014). Common steps in an ALS-based FMI are 1) manual stand delineation, 2) stratification of the stands into four or more tree-species and maturity-class specific strata, 3) ALS data acquisition, 4) measurements of some hundred field sample plots systematically distributed in the strata, 5) fitting of stratum-specific linking models for timber volume and other response variables, and 6) estimation of stand-level parameters. One main outcome of FMIs is a stand map or stand list that includes stand-level information on the dominant species and the estimated timber volume.

NFIs, on the other hand, collect data for regional or national statistics over several years according to a national systematic design. Such a sampling design results in an overall larger data set of field plot measurements at the large scale but a much smaller sampling fraction than in a FMI. Nevertheless, earlier studies have explored the use of NFI sample plot data with remote sensing for stand-level estimation of forest parameters. McRoberts (2008) achieved promising results using Landsat satellite imagery to bridge strategic inventories and FMIs in Minnesota, USA. Breidenbach et al. (2018) compared unit level and area level models and estimators based on NFI and DAP data. Maltamo et al. (2009) and Tuominen et al. (2014) used ALS data and Finish angle count NFI data with or without additional fixed radius sample plot measurements to estimate stand parameters and assessed estimation accuracy. While the use of NFI plots produced acceptable estimates and improved accuracies when used together with fixed radius plots, the NFI sample plot designs caused problems for practical application.

Other approaches combining NFI and remote sensing data focus on the creation of national forest resource maps by wall-to-wall mapping of forest parameters on nationwide scale. Early examples of such maps linked coarse optical satellite data with NFI sample plots as reference data (Reese et al., 2003; Gjertsen, 2007; Tomppo et al., 2008). In recent years, coverage with fine resolution 3D remote sensing data has increased drastically. On one hand, advances in soft- and hardware made it possible to compute large-scale 3D information from aerial imagery by means of DAP. Such 3D data have been used to create forest resource maps covering large regions or nations (Breidenbach et al., 2016; Bohlin et al., 2017; Rahlf et al., 2017; Astrup et al., 2019), using NFI-data as reference. On the other hand, large-scale ALS campaigns have been
or are currently being conducted in several countries, mainly aiming on the creation of accurate digital terrain models. While the remotely sensed data used in these maps are often not optimized for forest analyses and varying sensors, acquisition settings and conditions lead to variation in the ALS data (Næsset, 2009; Næsset and Gobakken, 2008), the large-area coverage enables the use of a great number of NFI sample plots in the fitting of forest parameter models. Examples of forest maps based on large-scale ALS data are Nilsson et al. (2016), Monnet et al. (2016) and Nord-Larsen and Schumacher (2012). In the following, we will denote these data sets “NFI-based maps”, and the regression models that link the ALS data with NFI plot data as “NFI models”. NFI-based maps typically contain forest parameters required in FMIs (Næsset, 2014).

Studies on the transferability of FMI models among areas (Tompalski et al., 2019; Karjalainen et al., 2019) suggest that models linking ALS metrics with variables of interest are relatively stable in most cases and often can be transferred between different areas but systematic errors may occur. These results are to be expected because synthetic estimators, e.g. estimators aggregating model predictions, only have small bias, if the local condition corresponds to the condition in the population used to fit the model (Rao and Molina, 2015, p. 36). Related to transferring models between different areas is the application of a large-scale model, as it is used for NFI-based maps, within a smaller area, where only few or no sample plots are located. While error analyses for NFI-based maps have been conducted on stand scale (e.g. Nilsson et al., 2016), it has not been studied how NFI-based map estimates compare to FMI estimates. If (synthetic) stand-level estimates of a NFI-based maps were similar to estimates of a traditional FMI approach, the NFI-based maps could used in the FMI. The use of the NFI-based map would then allow considerable cost saving by eliminating or reducing the need for field plot measurements.

The aim of this study is to compare the performance of a model used in a NFI-based map, namely the Norwegian national forest resources map SR16, and models used in a FMI in terms of accuracy of plot-level predictions and stand-level estimates. Furthermore, we evaluate utilizing additional local sample plots in the model of the NFI-based map (“adjusted NFI model”) in an attempt to improve local model accuracy.

2 Material and methods

2.1 Study area

The study area is in southeastern Norway, covering parts of the counties Innlandet and Viken (Figure 1). An FMI was conducted within the study area and covers the municipalities Våler and Elverum. The forests are dominated by Norway spruce (Picea abies (L.) Karst.) and Scots pine (Pinus sylvestris (L.)), while deciduous tree species are less frequent. For the current analysis, we focus on the FMI-stratum consisting of Norway spruce-dominated stands in the maturity classes “production forest” and “old production forest”, which comprise the oldest and economically most valuable stands. For simplicity, we will refer to the stratum of interest as mature spruce forest. A description of the Norwegian maturity class system can be found in Breidenbach et al. (2020, Section 5.3.2).
Figure 1: Location of the study area and the NFI plots used in this study. Subdivisions within the study area indicate different ALS projects. The area covered by the FMI is highlighted in dark gray.

Figure 2: Approximate locations of the NFI and FMI plots within the FMI area and stands with a detailed inventory. Subdivisions indicate different ALS projects (A-C).
Table 1: ALS data acquisitions in the study area

| ALS project | Municipality | Sensor       | Point density (#/m²) | Acquisition time     |
|-------------|--------------|--------------|----------------------|----------------------|
| A           | Elverum      | Optech Titan | 5                    | May–June 2016        |
| B           | Våler        | ALS70-HP     | 2                    | June–October 2016    |
| C           | Elverum      | ALS70-CM     | 2                    | May–October 2016     |

2.2 Airborne laser scanning data

The ALS data used in this study were acquired as part of a campaign to create nationwide elevation models (Statens kartverk, 2018). An available FMI (Blom Norway AS, 2018, unpublished) had been conducted within the outline of three different acquisitions (Figure 2, Table 1). Additionally, data from other ALS acquisitions in southeastern-Norway (Figure 1) with varying sensors, point densities, and acquisition dates were used in the NFI models.

For each ALS project, ALS returns were extracted that intersected with the NFI and FMI sample plots. We used the existing national terrain model based on ALS data with a resolution of 1 m to subtract terrain elevation from the return elevation to obtain heights above ground, using bi-directional linear interpolation. ALS height metrics were calculated from the point clouds: mean height (zmean), height standard deviation (zsd), height percentiles (zp05, zp10, zp20, ..., zp90, zp95). Density metrics were calculated by dividing the distance between the lowest and the highest return into 10 bins with equal heights and calculating the percentage of returns above the lower bin threshold. We calculated these metrics for first returns (*_f) and for last returns (*_l) without a height threshold, and with a height threshold of 2 m (*_2m_f, *_2m_l). The percentage of all returns above 2 m (perc_n_2m) served as an additional density metric.

For mapping purposes, we used 16 x 16 m grid cells, that correspond approximately to the NFI and FMI plot sizes. For each grid cell we extracted the ALS returns and subtracted the terrain height. Subsequently, the same ALS metrics as for the sample plots were calculated wall-to-wall for each ALS project.

2.3 FMI data

Forest stand polygons were available as part of the FMI (Blom Norway AS, 2018), that were delineated by visual interpretation of remotely sensed data and classified into five strata based on tree species, site index and maturity class. A total of 20,427 stands with areas between 0.03 and 25 ha, covering a total area of 19,800 ha, were within the mature spruce forest stratum. Within these polygons, 402 systematically distributed sample plots in clusters with up to 3 x 3 plots were measured in 2017. 101 of these sample plots were located in mature spruce stands (Figure 2).

The FMI sample plots are circular and have an area of 250 m². All trees with a dbh ≥ 10 cm were registered. Heights were measured for approximately 10 trees per plot. From these tree measurements, we estimated plot-level timber volume following the methodology of the Norwegian NFI based on species specific volume models (Braastad, 1966; Brantseg, 1967; Vestjordet, 1967). For a detailed description of the volume estimation from tree-level measurements see Breidenbach et al. (2020, Section 5.2.1.1).
By convention we speak of *plot-level measurements* although we are aware of the model-related uncertainty.

The mean timber volume of the FMI was 51% and 13% larger than the mean timber volume of the NFI plots in the FMI area and the whole study area, respectively (Table 2).

### 2.4 FMI models

Following the methodology of forest management planning in Norway (Næsset, 2014), *FMI models* were fitted based on the estimated FMI plot timber volume measurements (2.3) using the methodology of the area based approach (Næsset, 2002). Log-log models were fitted for each ALS project using ALS metrics as explanatory variables.

\[
\ln vol_j = \beta_0 + \beta_1 \ln x_1 + ... + \beta_k \ln x_k + \varepsilon_j, \tag{1}
\]

where \(vol_j\) is the timber volume at FMI plot \(j\) and \(x_1, \ldots, x_k\) are the explanatory variables. To correct for transformation bias, \((0.5 \sigma^2)\) were added to the intercept before transforming predictions back to the original scale.

Explanatory variables for the log-log models were selected using a step-wise forward and backward selection scheme informed by the Akaike information criterion (AIC) (Table 3). The algorithm was allowed a maximum of four explanatory variables in addition to the intercept to avoid overfitting.

Accuracies of the models were assessed based on leave-one-out cross-validation (CV) of the modeling data using root-mean-squared deviance (RMSD, RMSD%) and mean deviance (MD, MD%), which were defined as

\[
RMSD = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (y_j - \hat{y}_j)^2}, \quad RMSD\% = \frac{RMSD}{\bar{y}} \cdot 100, \tag{2}
\]

\[
MD = \frac{1}{n} \sum_{j=1}^{n} (y_j - \hat{y}_j), \quad MD\% = \frac{MD}{\bar{y}} \cdot 100, \tag{3}
\]

where \(y_j\) is the timber volume observed at plot \(j\), \(\hat{y}_j\) is the predicted timber volume at plot \(j\), \(\bar{y}_j\) is the mean observed timber volume of all plots, \(n\) is the total number of plots.

Across all ALS projects, the (cross-validated) RMSD was 62 \(m^3ha^{-1}\) (19%) and the MD 2 \(m^3ha^{-1}\) (1%). Figure 3 illustrates the model fits for all three ALS projects at plot level. RMSDs and MDs using NFI data are given in the Results (Section 3.1).
Table 3: Model parameter estimates, RMSD and MD (based on leave-one-out cross-validation) of the FMI models.

| ALS project | Explanatory variables | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | RMSD (%) | MD (%) |
|--------------|-----------------------|-----------|-----------|-----------|-----------|-----------|----------|--------|
| A            | Intercept, zmean_l, d5_2m_f, d5_2m_l, zq20_l | 0.65      | 2.01      | -1.35     | 0.96      | -0.05     | 15       | 0      |
| B            | Intercept, zmean_l, zq10_f, zq10_l          | 2.26      | 1.70      | -0.10     | 0.15      |           | 22       | 1      |
| C            | Intercept, zmean_f, zmean_l, d9_2m_f, d9_l  | 2.62      | 1.01      | 0.55      | 0.42      | -0.31     | 20       | 1      |

Figure 3: Observed vs. predicted timber volume using FMI models. Predictions of the FMI plots were based on leave-one-out cross-validation.
2.5 NFI data

The 815 permanent sample plots of the Norwegian NFI (Breidenbach et al., 2020) in the study area were measured between 2014 and 2018 (Figure 1). A total of 244 of the plots belonged to the mature spruce stratum (see Table 2) of which 12 were in ALS project A, 17 in B, and 13 in C (Figure 1 and 2). The NFI sample plots are circular with an area of 250 m². On the sample plots diameters at breast height (dbh) and tree species of all trees with dbh ≥ 5 cm are registered. Tree heights are measured from approximately 10 trees per plot, which are sampled using weights based on diameter and distance to the plot center. Positions of the sample plot centers were measured using differential GPS and GLONASS.

Similar to the FMI data, timber volume was estimated following the methodology of the Norwegian NFI (see Section 2.3). The timber volumes were fore- and back-casted to summer 2017, when the FMI was conducted. To do so, we calculated the yearly increment from the recent two tree-level volume predictions and multiplied the increment by the time difference which was then added to the predicted timber volume stock at tree level. To adjust the NFI data to the FMI protocol, trees with dbh < 10 cm were discarded and the plots were stratified according to the FMI stratification. Single tree volumes were subsequently totaled at plot level, and estimates of timber volume per ha were calculated.

2.6 NFI model

The basis for the timber volume map within the NFI-based Norwegian forest resources map SR16 (Astrup et al., 2019) are linear mixed-effects models fitted to data from NFI sample plots of a larger region covered by available ALS data. Tree species specific models are fitted with timber volume as the response and ALS metrics as fixed effects. The ALS metrics used in the models are mean first return height above ground and a density metric. An identifier at ALS-project level is used as random effect to address differences in the sensors and the acquisition conditions. Because the within-group variance is observed to increase linearly with volume, heteroscedasy is modeled using a variance function.

We re-fitted a linear-mixed effects model for timber volume of mature spruce stands using the ALS and NFI data within the study area with the adjusted dbh threshold of 10 cm. We refer to this model as ("NFI model"). Fixed effects were $z_{\text{mean}, f}$ and $z_{\text{mean}, f}^2$, as well as perc.n.2m as a density metric. Before model fitting, 10 outliers that were likely affected by harvests were visually identified and removed by analyzing residual plots. The random effect on the ALS-project level for the slope of $z_{\text{mean}, f}$ was used.

The NFI model was formulated as

$$\text{vol}_{ij} = \beta_0 + (b_i + \beta_1) z_{\text{mean}, f_{ij}} + \beta_2 z_{\text{mean}, f_{ij}^2} + \beta_3 \text{perc.n.2m}_{ij} + \epsilon_{ij},$$  \hspace{1cm} (4)

$i = 1, \ldots, m, \quad j = 1, \ldots, n_i, \quad b_i \sim N(0, \sigma_b^2), \quad \epsilon_{ij} \sim N(0, \sigma^2_{\text{vol}_{ij}})$,

where $\text{vol}_{ij}$ is the timber volume at sample plot $j$ in ALS project $i$. $\beta_1, \beta_2, \beta_3$ are the fixed-effects parameters, $b_i$ is the random-effect parameter, $n_i$ is the number of sample plots within ALS project $i$, $m = 26$ is the number of ALS projects, $\sigma_b^2$ is the
Table 4: Parameter estimates of the mixed-effects model.

| Parameter estimates | 23.73 | 19.75 | 0.98 | -63.34 | 1.39 | 17.08 | A: -0.92, B: 1.45, C: -0.75 |

Figure 4: Observed vs. predicted timber volume ($m^3 ha^{-1}$) at the NFI plots using the NFI model. Predictions are based on leave-one-out cross-validation.

The estimated parameters and other characteristics of the NFI model are shown in Table 4. The CV RMSD of the NFI model was 21% with no systematic deviation (MD) based on all NFI sample plots. The RMSD on plot-level describes the uncertainty of the NFI-based map on pixel-level. The observed vs. CV-predicted timber volume is shown in Figure 4. RMSDs and MDs using FMI data are given in the Results (Section 3.1).

2.7 Adjusted NFI model: utilizing additional local sample plots for model improvement

We attempted to improve the local accuracy of the NFI based map by extending the modeling data set of the NFI model with local sample plots. Two data sets were

...
tested: (i) a combination of the NFI and all FMI sample plots and (ii) a combination of the NFI and a subset of FMI sample plot data. The subset of FMI sample plots was chosen based on the value of $z_{\text{mean}, f}$. A comparison of the NFI and FMI sample plots shows the presence of relatively more plots with higher volumes in the FMI data (Table 2). The FMI sample plots were therefore sorted based on the value of $z_{\text{mean}, f}$, and a number of plots were chosen from the top of this list, i.e. plots with the largest values of $z_{\text{mean}, f}$. By iterative testing and evaluating the improvement, the number of FMI sample plots selected to be combined to the NFI data was set to 7 per ALS project. Predictions of timber volume at the FMI sample plots for the calculation of accuracy measures were obtained using leave-one-out cross-validation for sample plots that were used in the modeling data. In the following, we refer to the resulting models as adjusted NFI models.

2.8 Comparison of the FMI and NFI models using stand-level estimates

Using the fitted models, timber volume was predicted for all 16 x 16 m cells of a grid covering the study area. To obtain synthetic estimates of stand-level timber volume we averaged the predictions of the grid cells with a center within the stands. To reduce the computational cost, we randomly selected 200 FMI stands per ALS project. A minimum area of 1 ha and a ratio $\sqrt{\text{area}/\text{perimeter}} > 0.2$, were used to reduce the edge effect of stand borders on the resulting estimates. We compared the synthetic stand-level estimates of the FMI models with those of the NFI models using RMSD and MD with $y_j$ and $\hat{y}_j$ as FMI and NFI model synthetic estimate, respectively (Equations 2 and 3).

2.9 Comparison to an independent forest inventory

As basis for a comparison to independent data, 61 sample plots in six forest stands were measured in ALS project B in 2018. The stands were selected from the delineated forest stand polygons with areas between 1.5 and 5.5 ha and a ratio $\sqrt{\text{area}/\text{perimeter}} > 0.2$. 10 to 11 sample plots were randomly selected from nodes of a 20 x 20 m grid intersecting with the stand boundaries. After the removal of one plot that fell on a forest road, one stand had nine sample plots, resulting in a total of 60 sample plots for the comparison.

In the field, plot center positions were measured using handheld GPS devices. The plots were circular with a radius of 8.92 m and were measured according to the NFI protocol (Section 2.5). The tree measurements were adjusted to the FMI protocol by discarding trees with dbh $\leq$ 10 cm, and single tree volumes were estimated following the methodology of the Norwegian NFI (Breidenbach et al., 2020). Individual tree volumes were totaled at plot level, and per-ha volume was calculated. Subsequently, stand-level estimates were obtained by averaging plot-level measurements (see Rahlf et al., 2014). Stand-level estimates based on these measurements are referred to as direct estimates. Direct estimates were treated as an observation.

Plot-level measurements ranged from 84 to 646 m$^3$ha$^{-1}$ and stand-level direct estimates from 154 to 380 m$^3$ha$^{-1}$. ALS data was clipped to the plot boundaries and plot timber volume was predicted using the ABA (see Section 2.2). RMSD and MD
Table 5: Differences between NFI model predictions and measurements at the FMI sample plots. RMSD and MD are based on independent validation for NFI data and cross-validation for FMI data.

| Modeling data | ALS project | RMSD (m$^3$ha$^{-1}$) | RMSD% | MD (m$^3$ha$^{-1}$) | MD% |
|---------------|--------------|------------------------|--------|---------------------|------|
| NFI           | A            | 83.14                  | 27     | 30.79               | 10   |
| NFI           | B            | 96.56                  | 25     | 46.08               | 12   |
| NFI           | C            | 78.38                  | 27     | 25.24               | 9    |
| NFI           | All          | 85.65                  | 27     | 33.22               | 10   |
| NFI & FMI     | A            | 76.69                  | 25     | 11.25               | 4    |
| NFI & FMI     | B            | 84.11                  | 22     | 16.60               | 4    |
| NFI & FMI     | C            | 69.56                  | 24     | 8.46                | 3    |
| NFI & FMI     | All          | 76.43                  | 24     | 11.78               | 4    |
| NFI & top 7 FMI | A         | 78.25                  | 26     | 9.61                | 3    |
| NFI & top 7 FMI | B     | 86.55                  | 23     | 27.28               | 7    |
| NFI & top 7 FMI | C     | 69.70                  | 24     | 7.11                | 2    |
| NFI & top 7 FMI | All     | 77.78                  | 24     | 13.90               | 4    |

were calculated using Equations 3 and 2 modified by setting $y_j$ as the direct estimate and $\hat{y}_j$ as estimate based on the FMI, NFI or adjusted NFI model.

3 Results

3.1 Comparison of FMI and NFI predictions and estimates

We validated the FMI models using NFI plots in the FMI area resulting in a RMSD and MD of 26% (56 m$^3$ha$^{-1}$) and -4% (-8 m$^3$ha$^{-1}$), respectively. Similarly, the NFI model was validated using FMI plots, resulting in an RMSD and MD of 27% (86 m$^3$ha$^{-1}$) and 10% (33 m$^3$ha$^{-1}$), respectively (Table 5). The NFI model showed a slight tendency to underpredict timber volume for FMI plots with timber volume $>350$ m$^3$ha$^{-1}$, which was mostly visible in ALS project B but less so in ALS projects A and C (Figure 5 a).

To analyse if the NFI-based model could be improved by using additional local sample plots, we fitted models based on a combination of the NFI data and either all or a subset of the FMI data (see Section 2.7). Models fit to either of the combinations of NFI and FMI data resulted in decreased RMSDs and MDs in all ALS projects compared to the NFI model (Table 5, Figure 5), when using FMI data for validation. The largest improvements of RMSDs were achieved when adding all FMI sample plots to the modeling data. The RMSD decreased by 3 and MD by 6 percentage points, nearly reducing the systematic error to a third of the MD of the NFI model. The RMSD of the adjusted NFI model, where only a subset of the FMI sample plots were added to the NFI data, had similar properties as the model using all NFI and FMI plots, with even smaller MDs in ALS projects A and C.

We compared synthetic estimates of the FMI models, the NFI model, and the improved NFI models for a sub-sample of forest stands in the FMI area. In coherence with the predictions at plot level, estimates of the NFI model tended to be smaller
Figure 5: Observed vs. predicted timber volume ($m^3 ha^{-1}$) at the FMI sample plots; predictions derived from the NFI model based on (a) NFI data, (b) NFI and all FMI data, and (c) NFI data and the 7 FMI sample plots with the largest $z_{mean_f}$. 
Table 6: Differences between synthetic stand estimates of FMI model and the NFI models based on 200 randomly selected stands.

| Modeling data         | ALS project | RMSD ($m^3 ha^{-1}$) | RMSD% | MD ($m^3 ha^{-1}$) | MD% |
|-----------------------|-------------|-----------------------|-------|-------------------|-----|
| NFI                   | A           | 40.25                 | 15    | 23.67             | 9   |
| NFI                   | B           | 37.55                 | 12    | 25.95             | 8   |
| NFI                   | C           | 22.83                 | 10    | 15.72             | 7   |
| NFI                   | All         | 34.60                 | 13    | 21.86             | 8   |
| NFI & FMI             | A           | 32.56                 | 12    | 6.35              | 2   |
| NFI & FMI             | B           | 24.75                 | 8     | 1.68              | 1   |
| NFI & FMI             | C           | 13.75                 | 6     | 2.90              | 1   |
| NFI & FMI             | All         | 25.16                 | 9     | 3.71              | 1   |
| NFI & top 7 FMI       | A           | 32.91                 | 12    | 4.22              | 2   |
| NFI & top 7 FMI       | B           | 27.15                 | 9     | 10.85             | 4   |
| NFI & top 7 FMI       | C           | 13.91                 | 6     | 0.57              | 0   |
| NFI & top 7 FMI       | All         | 26.14                 | 10    | 5.21              | 2   |

than of the local FMI models. Only for stands with small timber volume the NFI model produced generally larger estimates. On average, this resulted in a MD of 8%. Estimates deviated least in ALS project C and most in A, regardless of the combination of sample plot data used for fitting the NFI model (Table 6).

The addition of local sample plots to the NFI data for the model fit reduced the differences between estimated based on NFI and FMI models, resulting in a smaller RMSD and especially smaller MD of the adjusted NFI models, compared to the NFI model. While the largest reduction was achieved when using all FMI sample plots, the reduction for the adjusted NFI model with 7 additional FMI sample plots was similar, with differences in RMSE and MD of 0–1 percentage points. The smaller deviation of the estimates of the adjusted NFI models from the estimates of the FMI models can also be seen in Figure 6.

3.2 Comparison to independent data

The FMI model, the NFI model and the adjusted NFI model predictions were validated using an independent forest inventory in ALS project B. The adjusted NFI model was fitted using NFI data and the 7 FMI plots with the largest measured timber volume. Of the three models, the NFI model performed best at stand and at plot level. At plot level, the NFI model and the adjusted NFI model produced smaller RMSEs than the FMI model (Table 7). Similar results were obtained at stand level, when the sample plots were aggregated within the 6 stands, RMSEs and MDs were smallest for the NFI and adjusted NFI model prediction. RMSEs were smaller at stand level than at plot level, while MDs had similar values.
Figure 6: Comparison of synthetic stand-level timber volume estimates ($m^3ha^{-1}$) resulting from the FMI and NFI models. Regional NFI model estimates are derived from models (ref) based on (a) NFI data, (b) NFI and all FMI data, and (c) NFI data and the 7 FMI sample plots with the largest $z_{mean,f}$. 
Figure 7: Comparison of plot-level predictions and stand-level estimates to an independent forest inventory in ALS project B.

Table 7: Differences between plot and stand-level estimates of the NFI and FMI models and direct estimates of a independent validation inventory

| Level  | Model              | n  | RMSD ($m^3ha^{-1}$) | RMSD%  | MD ($m^3ha^{-1}$) | MD%  |
|--------|--------------------|----|---------------------|--------|-------------------|------|
| plot   | FMI model          | 60 | 65                  | 24     | -34               | -13  |
| plot   | NFI model          | 60 | 48                  | 18     | -7                | -2   |
| plot   | adjusted NFI model | 60 | 55                  | 21     | -29               | -11  |
| stand  | FMI model          | 6  | 40                  | 15     | -34               | -13  |
| stand  | NFI model          | 6  | 13                  | 5      | -6                | -2   |
| stand  | adjusted NFI model | 6  | 30                  | 11     | -29               | -11  |
4 Discussion

We compared the accuracies of a NFI model, as it is used in a NFI-based map linking ALS data and NFI sample plots, and local FMI models for timber volume of mature spruce forest. The accuracy of the NFI model was similar to the FMI models at plot and stand level. The NFI model was slightly more accurate than the FMI models, when an independent data were used for validation. Here, the NFI model also showed a smaller systematic error than the FMI and the adjusted NFI models.

In a direct comparison of stand level estimates, differences between the FMI and NFI models could be observed but it is unknown if the FMI or NFI models are closer to reality. However, the differences between the FMI and NFI models were relatively small and had the same magnitudes as typical stand-level RMSDs of ALS models (Næsset et al., 2004). While no clear improvement of the NFI model accuracy could be observed, when using additional local sample plots, it reduced the deviations of stand-level estimates based on the NFI-model and the FMI-models, making the model estimates of the NFI model more similar to the estimates of the FMI model.

MDs of the NFI model at plot level, as well as the RMSD of the estimates of the stands with validation Inventory were in line with previously reported RMSDs for ALS data (Næsset et al., 2004; Rahlf et al., 2014). Other studies on NFI-based maps for timber volume reported similar or lower plot-level accuracies (Nord-Larsen and Schumacher, 2012; Monnet et al., 2016; Nilsson et al., 2016). Analysing the use NFI plots in ALS based forest management inventories, Maltamo et al. (2009) reported a larger stand-level RMSD of 19.66% and a similar MD of -1.13%, compared to the NFI model accuracies.

Testing the application of a regional model to smaller areas, Noordermeer et al. (2019) fitted local and regional multiplicative regression models using data from multiple FMIs. Accuracies for timber volume in productive mature forests were slightly higher for local than for regional models with RMSDs similar to the RMSDs obtained in this study. Tompalski et al. (2019) analyzed the transferability of ALS models by predicting forest parameters using different ALS data within the same study area in Canada. Unlike to our findings, they reported only minor changes in RMSD and MD for ordinary least square models on plot level using CV. However, differences in the ALS data were simulated by reducing point densities, which has been reported to have only limited effects on model accuracies (Gobakken and Næsset, 2007; Jakubowski et al., 2013).

We used two approaches to compare accuracies of the models: Using the training data of the other model as validation data with CV for the additional sample plots of the adjusted NFI models, and using an independent forest inventory as reference data set. The independent forest inventory allowed a comparison of accuracies based on the same reference data. Since the independent forest inventory was located in only one ALS project, the use of the FMI data served to assess differences in the NFI model accuracies between the ALS projects. A reason for the differences between accuracies obtained with the two approaches might be the distribution of the response variable in the data. While the stands of the independent forest inventory lie around the center of the distribution of timber volume of the NFI data, the FMI sample plots show a larger range, extending over the maximum timber volume of the NFI sample plots. The largest difference between the model validation using CV and an independent...
forest inventory was observed in the values for MD. While these differences could be observed, in general, both approaches provided the same results.

The validation of the NFI-based map in this study is based on the comparison to a single FMI across three ALS projects. As the differences in accuracies of the NFI model between the ALS projects suggest, an exhaustive analysis on differences between NFI and FMI accuracies would need to include multiple FMIs from different regions. Additionally, more parameters, e.g. basal area, tree height, need to be tested for the use in an operational FMI.

The stand-level accuracies in this study are based on 60 plots within six forest stands. Interpretation of these accuracies should therefore be carried out carefully. However, even though estimation of stand-level parameters is the aim of remote sensing applications in FMIs, the analysis of plot-level accuracy is common in FMI research studies ((Næsset, 2014). In addition, the accuracy improvement when aggregating plot-plot level predictions at stand-level are in line with previous studies (Rahlf et al., 2014; Bohlin et al., 2017).

To analyze the influence of few additional FMI plots on the NFI model, plots were selected based on their value of \(z_{\text{mean}}\). The result showed that these plots slightly improved the NFI model accuracy and reduced the systematic error only for plot-level predictions when FMI data was used for validation, and the improvement differed between the ALS projects. Reasons might be non-optimal selection of the local plots. Methods based on sample distributions and local conditions (Grafström et al., 2012) could be considered to improve sample plot selection.

In conclusion, the presented comparison shows that estimates of a NFI-based map can be similarly or more accurate than estimates of an FMI. The similar accuracies indicate that NFI-based maps can directly be used in FMIs for timber volume estimation in mature spruce stands, leading to potentially large cost savings with only small, if any, losses in accuracy. The addition of local sample plots when fitting an NFI model did not clearly improve the model accuracy.

References

Astrup R, Rahlf J, Bjørkelo K, Debella-Gilo M, Gjertsen A.-K, and Breidenbach J. Forest information at multiple scales: development, evaluation and application of the norwegian forest resources map sr16. Scandinavian Journal of Forest Research, 0(0):1–13, 2019. doi: 10.1080/02827581.2019.1588989. URL https://doi.org/10.1080/02827581.2019.1588989.

Blom Norway AS. Beregning av skogvariable basert på laserdata i elverum-våler 2018 [calculation of forest parameter based on als data in elverum-våler 2018]. techreport, 2018.

Bohlin J, Bohlin I, Jonzén J, and Nilsson M. Mapping forest attributes using data from stereophotogrammetry of aerial images and field data from the national forest inventory. Silva Fenn, 51(2):1–18, 2017.

Braastad H. Volume tables for birch. Meddelelser fra det Norske Skogforsoksvesen, 21 (1):23, 1966.
Brantseg A. Volume functions and tables for Scots pine. South Norway. (In Norwegian with English summary). *Meddr. Norske SkogforsVes.*, pages 695–739, 1967.

Breidenbach J, McRoberts R. E, and Astrup R. Empirical coverage of model-based variance estimators for remote sensing assisted estimation of stand-level timber volume. *Remote Sensing of Environment*, 173:274–281, 2016.

Breidenbach J, Magnussen S, Rahlf J, and Astrup R. Unit-level and area-level small area estimation under heteroscedasticity using digital aerial photogrammetry data. *Remote Sensing of Environment*, 212:199–211, 2018.

Breidenbach J, Granhus A, Hylen G, Eriksen R, and Astrup R. A century of national forest inventory in norway – informing past, present, and future decisions. preprint, 2020.

Gjertsen A. K. Accuracy of forest mapping based on Landsat TM data and a kNN-based method. *Remote Sensing of Environment*, 110(4):420–430, 2007. ISSN 0034-4257.

Gobakken T and Næsset E. Assessing effects of laser point density on biophysical stand properties derived from airborne laser scanner data in mature forest. In *ISPRS Workshop on Laser Scanning*, volume 200, pages 12–14, 2007.

Grafström A, Lundström N. L, and Schelin L. Spatially balanced sampling through the pivotal method. *Biometrics*, 68(2):514–520, 2012.

Jakubowski M. K, Guo Q, and Kelly M. Tradeoffs between lidar pulse density and forest measurement accuracy. *Remote Sensing of Environment*, 130:245 – 253, 2013. ISSN 0034-4257. doi: https://doi.org/10.1016/j.rse.2012.11.024. URL http://www.sciencedirect.com/science/article/pii/S0034425712004567.

Kangas A, Astrup R, Breidenbach J, Fridman J, Gobakken T, Korhonen K. T, Maltamo M, Nilsson M, Nord-Larsen T, Næsset E, and Olsson H. Remote sensing and forest inventories in nordic countries – roadmap for the future. *Scandinavian Journal of Forest Research*, 33(4):397–412, 2018a. doi: 10.1080/02827581.2017.1416666. URL https://doi.org/10.1080/02827581.2017.1416666.

Kangas A, Gobakken T, Puliti S, Hauglin M, and Næsset E. Value of airborne laser scanning and digital aerial photogrammetry data in forest decision making. *Silva Fenn*, 52(1):9923, 2018b.

Karjalainen T, Korhonen L, Packalen P, and Maltamo M. The transferability of airborne laser scanning based tree-level models between different inventory areas. *Canadian Journal of Forest Research*, 49(3):228–236, 2019.

Maltamo M, Packalén P, Suvanto A, Korhonen K, Mehtätalo L, and Hyvönen P. Combining als and nfi training data for forest management planning: a case study in kuortane, western Finland. *European Journal of Forest Research*, 128(3):305–317, 2009.

Maltamo M and Packalén P. Species-specific management inventory in Finland. In *Forestry Applications of Airborne Laser Scanning*, pages 241–252. Springer, 2014.
McRoberts R. E. Using satellite imagery and the k-nearest neighbors technique as a bridge between strategic and management forest inventories. *Remote Sensing of Environment*, 112(5):2212 – 2221, 2008. ISSN 0034-4257. doi: https://doi.org/10.1016/j.rse.2007.07.025. Earth Observations for Terrestrial Biodiversity and Ecosystems Special Issue.

Monnet J, Ginzler C, and Clivaz J. Wide-area mapping of forest with national airborne laser scanning and field inventory datasets. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B8:727–731, 2016. doi: 10.5194/isprs-archives-xli-b8-727-2016.

Næsset E. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sensing of Environment*, 80(1):88–99, 2002.

Næsset E and Gobakken T. Estimation of above-and below-ground biomass across regions of the boreal forest zone using airborne laser. *Remote Sensing of Environment*, 112(6):3079–3090, 2008.

Næsset E, Gobakken T, Holmgren J, Hyvypä H, Hyvypä J, Maltamo M, Nilsson M, Olsson H, Persson Å, and Söderman U. Laser scanning of forest resources: the nordic experience. *Scandinavian Journal of Forest Research*, 19(6):482–499, 2004.

Næsset E. Effects of different sensors, flying altitudes, and pulse repetition frequencies on forest canopy metrics and biophysical stand properties derived from small-footprint airborne laser data. *Remote Sensing of Environment*, 113(1):148–159, 2009.

Næsset E. Area-based inventory in Norway—from innovation to an operational reality. In *Forestry Applications of Airborne Laser Scanning*, pages 215–240. Springer, 2014.

Nilsson M, Nordkvist K, Jonzén J, Lindgren N, Axensten P, Wallerman J, Egberth M, Larsson S, Nilsson L, Eriksson J, and Olsson H. A nationwide forest attribute map of sweden predicted using airborne laser scanning data and field data from the national forest inventory. *Remote Sensing of Environment*, 2016.

Noordermeer L, Bollandsås O. M, Ørka H. O, Næsset E, and Gobakken T. Comparing the accuracies of forest attributes predicted from airborne laser scanning and digital aerial photogrammetry in operational forest inventories. *Remote Sensing of Environment*, 226:26–37, 2019.

Nord-Larsen T and Schumacher J. Estimation of forest resources from a country wide laser scanning survey and national forest inventory data. *Remote Sensing of Environment*, 119:148–157, 2012.

Pinheiro J, Bates D, DebRoy S, Sarkar D, and R Core Team. *nlme: Linear and Nonlinear Mixed Effects Models*, 2019. URL https://CRAN.R-project.org/package=nlme. R package version 3.1-141.

R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2019. URL https://www.R-project.org/.
Rahlf J, Breidenbach J, Solberg S, Næsset E, and Astrup R. Comparison of four types of 3D data for timber volume estimation. *Remote Sensing of Environment*, 155:325–333, 2014.

Rahlf J, Breidenbach J, Solberg S, Næsset E, and Astrup R. Digital aerial photogrammetry can efficiently support large-area forest inventories in norway. *Forestry: An International Journal of Forest Research*, 90(5):710–718, 2017. doi: 10.1093/forestry/cpx027.

Rao J. N. K and Molina I. *Small Area Estimation*. Wiley, 2nd edition edition, 2015.

Reese H, Nilsson M, Pahlén T. G, Hagner O, Joyce S, Tingelöf U, Egberth M, and Olsson H. Countrywide estimates of forest variables using satellite data and field data from the national forest inventory. *AMBIO: A Journal of the Human Environment*, 32(8):542–548, 2003.

Statens kartverk. Produktspesifikasjon fkb-laser versjon 3.0. techreport, 2018. URL https://register.geonorge.no/data/documents/Produktspesifikasjoner_FKB-Laser_v1_fkb-laser-v30-2018-01-01_.pdf.

Tompalski P, White J. C, Coops N. C, and Wulder M. A. Demonstrating the transferability of forest inventory attribute models derived using airborne laser scanning data. *Remote Sensing of Environment*, 227:110–124, 2019. doi: 10.1016/j.rse.2019.04.006.

Tomppo E, Haakana M, Katila M, and Peräsaari J. *Multi-source national forest inventory: methods and applications*, volume 18. Springer Science & Business Media, 2008.

Tomppo E, Gschwantner T, Lawrence M, and McRoberts R. E, editors. *National Forest Inventories*. Springer Netherlands, 2010. ISBN 978-90-481-3232-4 978-90-481-3233-1. doi: 10.1007/978-90-481-3233-1.

Tuominen S, Pitkänen J, Balazs A, Korhonen K. T, Hyvönen P, Muinonen E, and others. NFI plots as complementary reference data in forest inventory based on airborne laser scanning and aerial photography in finland. *Silva Fennica*, 48(2):983, 2014.

Vestjordet E. Funksjoner og tabeller for kubering av stående gran [functions and tables for volume of standing trees. Norway spruce]. *Meddelelser fra Det norske Skogforsøksvesen*, (22):543–574, 1967.