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Remote sensing and forest inventories in Nordic countries – roadmap for the future

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ABSTRACT
The Nordic countries have long traditions in forest inventory and remote sensing (RS). In sample-based national forest inventories (NFIs), utilization of aerial photographs started during the 1960s, satellite images during the 1980s, laser scanning during the 2000s, and photogrammetric point clouds during the 2010s. In forest management inventories (FMI), utilization of aerial photos started during the 1940s and laser scanning during the 2000s. However, so far, RS has mostly been used for map production and research rather than for estimation of regional parameters or inference on their accuracy. In recent years, the RS technology has been developing very fast. At the same time, the needs for information are constantly increasing. New technologies have created possibilities for cost-efficient production of accurate, large area forest data sets, which also will change the way forest inventories are done in the future. In this study, we analyse the state-of-the-art both in the NFIs and FMIs in the Nordic countries. We identify the benefits and drawbacks of different RS materials and data acquisition approaches with different user perspectives. Based on the analysis, we identify the needs for further development and emerging research questions. We also discuss alternatives for ownership of the data and cost-sharing between different actors in the field.

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Introduction

Forest information is collected at many levels and for many purposes. Typically, a sampling-based national forest inventory (NFI) is carried out to provide national- and international-level statistics (e.g. Tomppo et al. 2010; Tomppo et al. 2011; Fridman et al. 2014). These statistics are used, for example, to form national or regional forest programmes, sustainability assessments, investment calculations for forest industry, strategic-level planning in general, and reporting to international conventions. Historically, the NFIs focused on wood resources. The main reason for starting forest inventories in Nordic countries was the fear of non-sustainable use of the forest resources in the late 1800s. Today, NFIs provide information on several major ecosystem services (see Hansen and Malmaeus 2016; Mononen et al. 2016), such as provision of material to industry, bioenergy, biodiversity, and changes in carbon pools (see e.g. Chirici et al. 2012; Rondeux et al. 2012).

At the forest holding level, spatially explicit forest data are needed, for instance, to support forest owners in their strategic planning as well as aid decision-making pertaining to harvests and silvicultural measures. Forest management inventories (FMIs) carried out for this purpose have traditionally been based on various proportions of visual assessments in the field and interpretation of aerial photos (e.g. Næsset et al. 1992; Ståhl 1992; Koivuniemi and Korhonen 2006). More recently, forest resource maps based on airborne laser scanning (ALS) are being used for FMI (e.g. Maltamo and Packalen 2014; Næsset 2014). Besides the forest owners, FMI data have typically been available only to the organization that has made the forest management plan or conducted the FMI, or to organizations that the land owner has given permission to access the data. There are, however, increasing demands that FMI data, when financed by the government, become public property.

Historically, NFIs and FMIs (holding or stand level) have been two separate activities carried out by different actors in the forest sector. However, while the primary purpose of NFI plots is to produce statistical estimates, they are today often also used as training data for producing nationwide wall-to-wall raster-type forest resources maps based on either satellite images, laser scanning, or photogrammetric point cloud data (Tomppo 1990; Nord-Larsen and Schumacher 2012; Nilsson et al. 2017; Bohlin et al. 2017; Tuominen et al. 2017). They are typically less accurate and/or less detailed than FMI data, but freely available also for other users than the forest owner. Such maps are currently available and/or under development in all Nordic countries.

The forest resource maps based on NFI and FMI can, in principle, be used for the same purposes to the extent that they provide the necessary biophysical parameters that are required in the subsequent planning process. For instance,

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the forest owners associations can use the maps in management and planning of individual operations such as contracting of harvests. In addition, forest companies can use them in the optimization of bucking of the logs (e.g. Kivinen 2004), planning of wood procurement and logistics, planning of timber trade and harvests based on current demand, or selecting the optimal use for each batch of timber. Accurate information would reduce the need for pre-harvest inventories and then possibly introduce significant cost savings. In addition to forest resources maps, operational planning would benefit from maps about terrain accessibility (e.g. Ågren et al. 2014). More accurate information on root rot, fire, or wind throw risk in each stand would also help in selecting measures to mitigate risk factors.

In recent years, the availability of three-dimensional (3D) data for large areas has increased dramatically through national or large area laser scanning campaigns that have been carried out in many European countries. Increased processing power combined with improved photogrammetric software has made it possible also to obtain national aerial photogrammetric point clouds as a low-cost by-product of existing national aerial photogrammetric campaigns. Furthermore, for example, Sentinel 2 and Landsat satellites produce freely available data with short intervals. In future, also 3D data satellite missions may be more used in practical forest inventory. The availability of large-scale 3D data gives a previously non-existing possibility for using NFI plot data as ground reference data for development of both forest resources maps and statistics that simultaneously satisfies information requirements at multiple scales.

Linking the worlds of NFI and forest management planning raises a series of interesting questions related to data ownership, and who should pay for the data and products. Furthermore, it raises questions related to who benefits from data, and which quality is needed to realize the potential benefits. Typically, the quality of data has only been analysed through its precision and accuracy. In recent years, it has been noted, however, that the quality should be measured in terms of benefits obtainable from the data, i.e. through analysing the usefulness of the data in a given decision-making problem or a work process. Such analyses have been carried out using cost-plus-loss analysis (e.g. Eid et al. 2004) or value-of-information analysis (Ståhl et al. 1994; Kangas 2010; Kangas et al. 2014).

In this paper, we review the developments in Denmark, Finland, Norway, and Sweden with respect to the use of remote sensing (RS) data in forest inventories, identify challenges, and make recommendations for potential future directions. We base this analysis on potential decision problems where the NFI and FMI data might be useful as decision support, and the characteristics of the data that are most important for those decision problems.

Specifically, the aims of the paper are:

(1) to describe the current practices of forest data acquisition in the Nordic countries;
(2) to identify drawbacks and benefits of new technologies, field data collection methods, and estimation techniques in making mutual benefits between NFIs and FMIs possible;
(3) to identify benefits and drawbacks of forest information acquired with different approaches for the different uses of the data;
(4) to discuss issues related to the ownership of data and sharing of data acquisition costs;
(5) to identify possible avenues to improve the current systems to better meet the requirements.

State-of-the-art and future plans in data acquisition in Nordic countries

Historical development of NFIs

Regulations on the use of the forest resources in Nordic legislation date back to earlier than the thirteenth century. Already in the early sixteenth century, export of sawn wood was prohibited from Norway, partly to secure domestic (Denmark–Norway) supply and partly to avoid over-exploitation of the

Table 1. Development of NFIs in Nordic countries.

	Pre-sampling era	Field sampling era	RS era
Denmark	National Forest Census was carried out roughly every 10 years from 1881 to 2000 based on questionnaires sent to forest owners.	The first national sample-based forest inventory was initiated in 2002.	Satellite images were used for a reference to the questionnaire surveys between 1990 and 2011. Lidar data used for mapping the forest resources 2006–2007.
Finland	A visual assessment was carried out in Finland in the nineteenth century (von Berg 1859, (republished 1995)).	The first forest inventory based on strip sampling was carried out 1921–1924 (Ilvessalo 1927). Cluster sampling has been used since the 5th NFI 1964–1970 (Kuusela and Salminen 1969).	Aerial photographs used in a two-phase sampling procedure in Lapland (Poso and Kujala 1971). Satellite images used for multi-source forest inventory for mapping and for municipality level results since the 1980s (Tomppo 1990).
Norway	The first nationwide subjective assessment was started in 1739 (Fryjordet 1968). The intention was to conduct a full NFI, but the survey became a more subjective description of the state of the resources (Nissen 1937).	An NFI following modern sampling principles (strip survey) was started in 1919.	Satellite images for mapping the forest resources (Gjertsen 2007). Lidar and/or photogrammetric data used for mapping and estimation (Breidenbach and Astrup 2010; Rahlf et al. 2014).
Sweden	In 1735 the Swedish county governors were ordered for the first time to report to the government on the state of the forests in their counties (Anon. 1914).	The first NFI based on strip survey 1923–1929 (Thorell and Östlin 1931; SOU 1932). Cluster sampling has been used since the 3rd NFI 1953–1962 (Ranneby et al. 1987).	Satellite images for mapping the forest resources 2000–2015. Lidar and/or photogrammetric data used for mapping since 2016 (Nilsson et al. 2017).

forest resources. Also from early on, it was known that sustainable forest management requires forest information (e.g. Hartig 1795; Cotta 1804).

As a result in all Nordic countries, subjective forest resources assessments were carried out already during the eighteenth and nineteenth centuries (Anon 1914; Det Statistiske Departement 1925; Nissen 1937; Fryjordet 1968; von Berg 1995). Due to the fear of over-exploitation, i.e. that the extraction of wood exceeded the growth, the focus in the early assessments was on growth rather than standing volume. It was also one of the motivating arguments for the establishment of the NFIs some years later (Table 1). Internationally, it is likely that the first discussions on the global forest resource situation took place in Paris during the World Fair in 1910 (von Segebaden 1998).

RS was also used in the forest inventories from early on, and new technologies were introduced whenever possible. In sample-based NFIs, aerial photographs were used during 1964–1984 in a two-phase sampling procedure in Lapland of Finland (Poso and Kujala 1971), but in other Nordic countries, aerial images were used as a background material only.

While RS has so far been only a little used in the estimation of regional NFI results or inference concerning their accuracy, RS has been widely used for mapping the forest resources. The first forest resources maps were produced in Finland based on satellite images starting from the 1980s (Tomppo 1990; Tomppo et al. 2011). Denmark was the first country producing a nationwide forest resource map based on laser scanning data (collected in 2006–2007) and trained with NFI data (Nord-Larsen and Schumacher 2012). The use of photogrammetric point clouds for mapping and estimation purposes was started in Norway in the 2010s (Breidenbach and Astrup 2012).

The current NFI systems

In all of the Nordic countries, the current NFIs are based on field plots and cover all ownership classes. In Norway, the plots are set out in a systematic fashion, but in the other Nordic countries, a systematic cluster sampling design is used (Table 2). Geographical stratification is used in all Nordic countries but Denmark. In all countries, a design-based approach is used for inference. Permanent plots are needed in order to get accurate information on the changes in the forests (Tomppo et al. 2011; Fridman et al. 2014). In all the Nordic countries except Norway, only part of the plots are permanent and are remeasured in subsequent inventory cycles, while the remaining plots are temporary. In all countries, the measurement cycle is five years. All of the plots are not necessarily visited in the field, if it is evident from RS material that they are non-forest plots. For instance, in Norway, circa 38% and in Denmark, circa 25% of the plots are visited in the field. The main characteristics of the forests are presented at Table 3.

RS is used mainly as a background material. For instance in Denmark, various Geographical Information System (GIS)-layers are used for initial identification of forest/other wooded land/non-forest land and for separating different types of land, e.g. protected forest from un-protected or land on water procurement areas. Likewise, in Sweden and Finland, GIS-layers are used for separating protected forest from unprotected. In Finland, also official statistics on the land area are utilized as auxiliary information. In Norway, aerial images and maps are used to assess indications that non-forested sample plots have been changed to forested ones before field crews are sent out. Even though the main use of RS is background material, it is useful for estimation in smaller areas such as for producing municipality-level results (e.g. Gjertsen et al. 2000; Tomppo et al. 2011).

Organization of forest NFIs

In Denmark, the responsible organization for the NFI is the Department of Geosciences and Natural Resource Management at University of Copenhagen (IGN). The contract for the NFI in Denmark does not include funding for employing RS data for making forest maps. Consequently, mapping of forest resources from remotely sensed data has been limited to individual campaigns, when funding through research proposals has been found. In Finland, the responsible organization is Natural Resources Institute Finland (Luke), in Norway, the NFI Department at the Norwegian Institute of Bioeconomy Research (NIBIO), and in Sweden, the Swedish University of Agricultural Sciences (SLU). All of them are governmental organizations independent from practical forestry (i.e. funded solely by the government). All these organizations provide data for official statistics, although their official status varies. In Denmark, for instance, IGN is not an official provider of statistics, but SLU in Sweden is.

The future of NFI systems

RS data are currently not used in defining sampling designs or estimation at the regional level, but in the future, it is likely that more and more RS material is used for both. In Sweden and Finland, selecting the clusters using the so-called local pivotal method to ensure that a balanced sample is tested (Grafström et al. 2014, 2017), and plans to replace the systematic sampling design in the future exist. Model-assisted and post-stratified sampling methods to increase the accuracy are being tested (e.g. Ståhl, Holm et al. 2011; Saarela, Grafström, et al. 2015; Kangas et al. 2016; Myllymäki et al. 2017). Adopting these methods to operational NFI requires further tests to make sure that the methods are feasible, i.e. suitable wall-to-wall auxiliary information is available for the whole country, and that the method is applicable for all the variables of interest in an NFI. There are no plans at the moment to use the mode-based approach in operational NFI in any of the countries, but tests are carried out (e.g. Gregoire et al. 2011; Saarela, Schnell, et al. 2015). In Norway, also small-area estimation for automatically segmented stands is of interest (Breidenbach et al. 2015).

Table 2. Current NFI design in the Nordic countries.

	Method used	Number of strata	Cycle	*N* of plots per year	Use of differential GNSS	Proportion of permanent clusters	Minimum reporting unit
Denmark	Cluster sampling	–	5 years	8600		33%	Region (NUTS3)
Finland	Stratified cluster sampling	6	Panel system of 5 years	15,000	Since 2014 100%	60%	District (landskap)
Norway	Stratified systematic sampling	4	Panel system of 5 years	4400	Currently 50%. Measurement campaign ongoing.	100%	County (fylke)
Sweden	Stratified cluster sampling	5	Panel system of 5 years	10,000	From 2017 onwards	65%	County (län)

Historical development of forest management planning inventories

While the reasoning behind the NFIs is in securing the sustainable use of forest resources, the goals of FMI are to activate the forest owners and enhance the utilization of forest resources (e.g. Tikkanen et al. 2010). Forest management requires information on all stands, and therefore, the FMI is based on inventory by compartments (Loetsch and Haller 1973, p. 7–9). Selecting a sample from all stands is too expensive, and therefore visual assessments have been widely used to produce characteristics such as basal area and height by tree species (Koivuniemi and Korhonen 2006). In Norway, the visual assessment in the field was the main method until the late 1970s and in Finland, it was the main method until 2008. In Sweden, the visual assessment of each stand in the field is still the most common method, but it is used with the aid of air photo interpretation.

Aerial photographs have been used in the FMIs in the Nordic countries since at least the late 1940s (Fryjordet 1962, p. 258) for stand delineation, as the delineation of stand borders became much easier with the aerial photographs, and for visual interpretation. From the early 1980s and until airborne lasers took over around 2002, manual assessment and measurements in photogrammetric work stations constituted the main method in Norway, and stereo observations and measurements guided the determination of all needed stand variables, at least in mature forests (Næsset 2014). Assessments in photogrammetric work stations with a minimum of field checks were also much used in Sweden from the 1980s until laser scanning took over three decades later.

Current forest management planning inventories

Aerial images are still commonly used for stand delineation in all countries, and visual interpretation is also used in Norway. In Denmark and Sweden, currently, most forest management plans are made by combining field work and interpretation of digital orthophotos.

Table 3. The main features of the Nordic countries.

	Denmark	Finland	Norway	Sweden
Total land area (km^2)	43,098	303,900	323,782	407,339
of that, proportion of productive forest (%)	15	67	27	58
of that, proportion of private forests (%)	74	61	88	51
Total volume (mio m^3)	132	2400	1109	3273
Annual gross increment (mio m^3)	7	108	26	123

Since the 2010s, laser scanning has been the main data source for FMI inventory and for stand delineation in both Finland and Norway (Næsset 2007, 2014; Maltamo and Packalen 2014). The inventories are carried out according to the area-based approach based on ALS data and field plots. It means that forest characteristics are predicted for an area of a grid cell rather than for a single tree. The forest variables are predicted using statistical modelling, typically *k* nearest neighbours imputation or regression modelling (Næsset 2004; Packalén and Maltamo 2007). Typically, three to six strata are used for collecting the field data. Stratification is used to ensure enough variation in the forest characteristics in the modelling data (Næsset 2004). In Norway or Finland, NFI plots have not been used as the training data for FMI inventory so far.

In Denmark and Sweden, to an increasing degree, map products from laser scanning are being used in producing the FMI data by complementing it with additional data. In both countries, nationwide raster databases with estimated forest variables that have been produced using ALS data and field reference plots from the NFI are freely available over the internet (Nilsson et al. 2017; Nord-Larsen et al. 2017, see the sub-section of map products). Furthermore, in Denmark, laser scanning point cloud data, digital terrain model (DTM), and crown height model (CHM) are freely available. In Sweden, several of the large forest companies have also made, or ordered, own products from laser scanning data and have their own field plots in the same way as in Norway and Finland.

Organization of forest management planning inventories

Existence of recent (less than 10–15 years old) forest management plans is a prerequisite for forest certification in all countries, details depending on the certification system applied. While the methods have been fairly similar in all Nordic countries, there are clear distinctions concerning who pays for the data, who has access to the data, and who organizes the collection of the data (Table 4).

In the most recent assessment in Denmark, only about 35% of the forest owners had a short-term (1–5 years) management plan and 25% had a long-term (5–20 years) plan (Nord-Larsen et al. 2014). However, for holdings with more than 100 hectares forest, 66% had a short-term and 54% had a long-term plan. Forest management planning and inventories are commonly carried out by private companies, which are typically responsible for the daily management of smaller forest estates.

Table 4. Current FMI organization in the Nordic countries.

	Method used	Who pays	Subsidies available	Coordination
Denmark	Visual assessment of aerial photos in combination with field measurements	Forest owner	No	No
Finland	Area-based laser scanning	Government (computer-suggested treatments) Forest owner (forest plan)	Data collection fully paid by public funds	Yes, centralized data collection
Norway	Visual assessment of aerial photos or area-based laser scanning	Forest owner	Yes (currently about 57%)	Yes (by the region forester)
Sweden	Visual assessment of aerial photos	Forest owner	No	No

In Finland, the Forestry Centre is collecting data for management plans in private forests. Besides biophysical forest variables, the inventory includes information on immediate tending needs and cutting possibilities. The inventory is funded by government budget (Table 4). However, the forest owners pay for the additional costs of making a management plan that accounts for the forest owner's specific aims for the forest management, and includes estimates for future forest growth and development. The actual holding-level management plan can be bought in the private market from commercial actors who may or may not use the data provided by the Forestry Centre. The Forestry Centre is responsible for the field plot data collection, and the field data are processed using Luke's automated calculation system. Private companies produce the forest resource data in raster format. A bidding process is used to select the companies for the production of the data in given regions. At 2009, the plans less than 10 years old covered 46% of the private forest area (Metla Statistics 2011).

In Norway, forest management planning and inventories are normally carried out by private forest inventory companies. The coordination of many owners within a region is required to keep the cost of data acquisition at a reasonable level. According to the Norwegian Agriculture Agency, the proportion of forest area participating in joint inventories across individual properties has been 70–95% in the period 2012–2015 and is increasing. The Swedish forest agency made a general forest inventory of most private estates between 1982 and 1993. With the exception of this period, the mapping for forest management planning in Sweden has been done on behalf of the forest owners, without coordination with nearby estates. In Sweden, plans are often made by forest owners associations, consultants, or by the forest companies that buy wood from the forest owners, covering 27 million hectares according to the Swedish Forest Agency.

Future of forest management planning inventories

There are plans for improving the FMI in the future in each of the countries. For instance in Denmark, the new growing stock and biomass maps based on NFI plots and ALS data include segmentation of the forest area into "forest stands" (Nord-Larsen et al. 2017). The segmentation along with volume estimates may be used for forest management planning. It is possible that the ready access to new data and technologies will increase the popularity of forest management planning in spite of the lack of subsidies to support it.

In Finland, the largest change in the near future is related to the availability of the data. In the near future, the FMI data in raster format will become freely available to all actors. Currently, the data are updated based on the forest owners informing the Forestry Centre about their plans to harvest, but new updating procedures are being developed. If the developed methods prove to be feasible, cuttings will be updated in the database using information from forestry operators and RS change detection. The technology for using information from forest operators is available, but the operational usage of this data requires that all operators are committed to provide the data.

In Norway, the use of NFI field plots in FMIs will be studied, as well as the use of external models ("external" in time, space, and technology) in traditional FMI. Also of interest is the use of photogrammetric and multi-temporal 3D data in FMI. Inclusion of all forest land in the estimation process of an FMI based on 3D data is under development (not just the older forests; recently, regenerated forests have traditionally been inventoried by field work). This has already been tested in two to three regions. Sensor fusion, with 3D ALS or photogrammetric data combined with hyper- and/or multi-spectral data, will be tested in the future.

In Sweden, Lantmäteriet has in 2016 started to produce 3D point clouds from digital photogrammetry on a regular basis, which could be an aid for delineation of forest stands, estimates of growth on a grid cell level, and automated estimates. Automated estimates for small holdings will, however, also require coordination of field data collection, which does not exist yet. There are discussions among the forest practitioners and administration about renewed national laser scanning, as well as updating of the free product "Skogliga grunddata" (see the sub-section of map products), using data from laser scanning or digital photogrammetry, but no decisions have been taken yet.

In order to more automatically provide raster databases with estimated forest variables that have similar or better quality on the stand level than estimates based on traditional field methods, a regular supply of data from laser scanning will be needed. Some of the large forest companies will order laser scanning on their own, but for the large amount of forest owners to benefit from laser scanning, there is a need for coordination of the data acquisition. Such coordination is currently discussed, but no decisions have been taken yet.

Forest resources map products

RS material is widely used for mapping the forest resources. The maps cover all the land not in other use (such as agricultural or built area), including open mountain and bog areas, and they form the most important output of NFIs in addition to the regional and national statistics. NFI plots are also the most important training data for mapping: only in Finland, a national-level mapping process without NFI plots is going on. These maps can be used as a basis not only for FMI, but also to many other decision situations.

In mapping, forest variables of interest measured from the field plots are predicted for grid cells with no field measurements, based on the RS features of the cells. *K* nearest neighbour imputation has been widely used in Finland, but also in the other Nordic countries (e.g. Tomppo and Halme 2004). The main benefit of *k*-nn is that all characteristics can be estimated at the same time, using the same approach. By using *k*-nn, also assumptions concerning the shape of the relationship can be avoided. However, linear regression is also often used for the mapping purposes.

Optical satellite images (Landsat), laser scanning, and photogrammetric point cloud data are all used for producing forest resource maps. In Finland, a five-year national programme for aerial photographs has been decided on, and a similar programme for laser scanning is under preparation, which will further enhance the mapping. The Swedish Land Survey (Lantmäteriet) is running an ambitious national aerial photography programme and production of 3D point clouds from digital photogrammetry has started. Satellite scenes, including scenes from Sentinel 2, are stored in a free national satellite data archive, and will be used for national-level RS products. The details of currently available map products in the Nordic countries are presented in Table 5.

In Denmark, several mappings of the Danish forest area using Landsats 5 and 7 data (1990, 2000, and 2011) have been undertaken for making a reference between the results from older questionnaire-based forest surveys and the current NFI-based results. None of these contained other information than the forest area. Based on ALS data collected in 2006–2007, a wall-to-wall biomass map was produced for Denmark. The pixel size is selected so as to roughly correspond to the 706 m^2 NFI plots. Based on measurements on NFI sample plots and corresponding ALS metrics, parametric models were developed for predicting growing stock and above ground and total biomass. Using the models, a national forest resource map was produced. A new wall-to-wall ALS data set was collected in 2014–2015. Using much the same methods as with the 2006–2007 data, a forest resource map has been produced, including forest canopy height, forest growing stock, and biomass. Furthermore, the forest area has been automatically segmented into “forest stands” using various measures of height and variability of the normalized Digital Surface Model (nDSM).

In Finland, multi-source maps based on NFI plots are freely available. Data are produced in a cycle of two years, using most recent available optical (currently, mainly Landsat) satellite data and most recent NFI plots, updated for growth and cuttings. The data product includes: land-use class, site class, stand age, mean diameter, mean height, basal area, canopy cover, biomass by tree components and by species, and volume by timber assortments and by species. Main data users are forest industry for timber procurement and numerous research projects. At the pixel level, the RMSE of total volume is roughly 60% (Tuominen et al. 2017).

Management planning inventory data collected with laser scanning will cover private forests by 2020; these data are available to forestry operators (at nominal costs) if the forest owner allows it. There is an ongoing legislation process to make the data available without the permission from the forest owner. Mainly, the stand-level (polygon) data are used. The current cycle is 10 years but is planned to be intensified in the future (after 2020). These data are used for making management plans for private forest owners, monitoring of forest use (inspection tasks) by the Forestry Centre, and timber procurement by forest industry.

In Norway, Forest resource map (SR16) is available for parts of the country and is under development for the whole country. It is based on NFI data and image matching or ALS data as auxiliary information. It is a raster map which is approximately consistent with the NFI sample plot size of 250 m^2 and a vector map of segments. Segments were created by identifying homogeneous units of land from the auxiliary information used for the raster map by applying object-based image analysis (OBIA). The forest parameter prediction maps include timber volume, above and below ground living biomass, increment, mean height, and dominant tree species. Parametric models are used to predict the forest parameters and prediction intervals are displayed for each numeric map layer. Synthetic variance estimates (Breidenbach et al. 2015; Magnussen et al. 2016) are given as a measure of uncertainty for aggregated values within segments. According to the national aerial photography programme, aerial images covering approximately one-fifth of Norway will be acquired each year. The images will be used in image matching and will thus result in updated maps. In 2016, a national ALS programme was started and the available data will be used to increase the cover of SR16. Several studies were conducted to develop SR16 (Breidenbach and Astrup 2012; Rahlf et al. 2014).

SATSKOG is an older forest resources map based on Landsat data, existing maps and NFI data (Gjertsen 2007). It is a vector map with the parameters timber volume, dominating tree species, and stand development class. Vectors were created by identifying homogeneous units of lands from Landsat images using OBIA. The map is currently not updated.

In Sweden, “SLU forest map” has been made by SLU for the years 2000, 2005, and 2010 using Landsat and SPOT data trained with NFI plot data. Recently, the production for 2015 was started, where Sentinel 2 satellite data are combined with tree height data from digital photogrammetry. The data product includes: volume by tree species groups, above-ground tree biomass, basal area, basal area weighted mean diameter, and basal area weighted mean tree height. Main data users are authorities and numerous research projects.

“Skogliga grunddata” is made from a national laser scanning campaign performed by Lantmäteriet. SLU has on behalf of the Swedish Forest Agency made predictions of forest variables by using NFI plot data as ground references (Nilsson et al. 2017). Predicted variables are: stem volume, above-ground tree biomass, basal area, and basal area weighted mean diameter and tree height. These predictions are so far presented for all of Sweden except the alpine

Table 5. Current map products.

	Name of the product	RS material used	Publishing times	Coverage	Resolution	Field data	Availability for public
Denmark	Land use/land cover map	Landsat	1990, 2000, 2011	100%	30 m × 30 m	None	No
	Forest resource map	ALS data	2006–2007	100%	25 m × 25 m	NFI plots	No (Yes for research purposes)
	Forest resource map	ALS data	2014–2015	100%	25 m × 25 m	NFI plots	Yes
Finland	MS-NFI map	Landsat (Resourcesat 1 LISS-III, Spot)	2015, 2013, 2011	100%	16 m × 16 m	NFI plots	Yes (older maps exist but not published)
	FMI forest resources map	ALS data	Parts of country yearly	Full coverage 2020	16 m × 16 m	Special set of plots	No (legislation to open it under work)
Norway	SR16 Forest resources map	ALS/image matching data	2017	Trøndelag region available (ca. 50,000 km^2)	16 m × 16 m	NFI plots	Yes
	SATSKOG	Landsat	2007	100%	30 m× 30 m	NFI plots	Yes
Sweden	SLU forest map	Landsat	2000, 2005, 2010	100%	25 m × 25 m	NFI plots	Yes
	Skogliga grunddata	ALS data	2016	100% (Except alpine areas)	12.5 m × 12.5 m	NFI plots	Yes
	National Corine	Spot	2012	100%	10.0 × 10.0–25.0 × 25.0	NFI plots	Yes

areas. The forest agency has also acquired additional products from the national ALS data, like a high-resolution tree height raster, and a raster map showing wet areas.

In addition, a national, more detailed, version of the CORINE land cover thematic map has been made with 2000 as the base year (Hagner and Reese 2007). A new version is now being made using Sentinel 2 data and national ALS data trained with NFI plot data. Field data and photo interpreted data from National Inventory of Landscapes in Sweden (NILS) (Ståhl, Allard et al. 2011) in combination with subjectively selected training data will be used as reference data for the classification of mountainous areas. The production is made by Metria AB with support from SLU.

Drawbacks and benefits of NFI and FMI data collection materials and methods from different perspectives

NFI and FMI have clearly different aims: NFI aims at national, regional, or county-level statistics while FMI aims at operative planning on holding and stand level. These roles are changing due to development of RS and advances in estimation techniques. For example, in Finland, the multi-source NFI produces stand-level data usually produced by FMI (e.g. Haakana 2017), and Forestry Centre is providing municipality-level results, usually produced by NFI, based on FMI data. In the future, this may introduce cost savings, if FMI were carried out using maps based on NFI plots rather than separate set of plots (or with NFI plots complemented with some additional plots). It may also introduce confusion, if there are several sets of statistics with unclear methods and accuracy concerning the same areas.

We have identified different decision problems (Table 6) where forest resource data are used. Four of these are purely local, two purely regional, and one task has a local as well as a regional perspective. The local decision problems require information on location (i.e. a forest resources map), while the regional decision problems not necessarily do. Each of these cases has been analysed to identify the critical properties of the data needs, and the potential benefits and drawbacks of each of the methods. In what follows, we present the findings of the analysis.

RS materials and technology

The main benefit in satellite-based forest resources mapping is its high temporal resolution. It is possible to obtain new data more frequently than with any other relevant method available, which is very important for tasks where the timeliness is essential. It is possible to form a time series, or use multiple images from one year for producing a single map. Another important benefit is the possibility for large-scale data. Moreover, much of this material is freely available, like the Sentinel 2 images.

The satellite data, in combination with the field data from NFI, provide the possibility for automated mapping, as well as high spatial resolution. Possibilities to produce stand information would be much diminished without the possibility for automated mapping. The possibilities for automatization, as well as the spatial resolution are important qualities in addition to the temporal resolution.

On the other hand, the relatively low correlation between the commonly applied optical satellite image data and most forest variables is a serious drawback in most decision problems requiring localized information. For such decision problems, 3D data are much more relevant. However, in the future, it will be feasible to obtain 3D data from very high resolution (VHR) satellite images and synthetic aperture radar (SAR) images for large areas, which is interesting since these data are correlated with important forest variables (e.g. Yu et al. 2015). This would make the satellite images potential data sources also for decision problems requiring local information.

The main benefit in the 3D photogrammetric point cloud data compared to ALS data is that aerial images are acquired over large areas every year in the Nordic countries, and 3D point clouds can be obtained as a side product of this work. One potential benefit of these data is that the number of points per square metre can be higher than with the low-density ALS. On the other hand, all the points are from the surface of the tree canopies, and practically no information is obtained from the vertical distribution of biological material within the crowns.

The 3D photogrammetric point clouds might, depending on the forest structure, produce estimates that are almost as good as those made from ALS point cloud data (Gobakken

Table 6. The drawbacks and benefits of different forest information sources from the point of view of given decision problems.

Data acquisition methods						
Decision problem and specific examples	Critical properties of data for the task	Sampling-based field inventory (NFI)	Satellite images – Finland (MS-NFI) – Sweden (*k*-nn map) – Sweden (satellite data change detection)	3D point cloud from aerial photos – Norway (NFI)	ALS – Finland (separate management inventory) – Norway (separate management inventory) – Sweden (NFI)	Traditional FMI (visual assessment, aerial images) – Sweden – Norway – Finland (where ALS not yet available)
(I) Inspection of forestry operations (for forest law) – detection of clear cuttings – monitoring the regeneration after clearcutting – detection of thinnings – monitoring if the thinning regimes are followed – monitoring of removal of wind-thrown trees after storms	– Timeliness is the most critical property – Non-detection is the biggest source of uncertainty – Over-estimation of changes leads to inefficiency	+ Produces regional information (with reliability estimate) on how well forest law is followed – No stand-level data	+ Possibility for annual monitoring – Data is often outdated (1–2 years) due to data availability	– The whole country cannot be covered in a short time – It takes more than a year to produce the map	– The whole country cannot be covered in a short time – It takes more than year to produce the map	+ Detection of thinnings and wind throws easy visually – Costly – Timeliness a serious problem
(II) Formulation of forest policies and monitoring of sustainability – can we increase cuttings? – is forestry sustainable? – is silviculture and forest management at good level? – are the environmental values considered in forestry operations – are cuttings a threat for important habitats/ forest types – change monitoring	– Unbiased – Known reliability – Timeliness – Relevant information content	+ Possibility for unbiased estimates + Possible to estimate reliability + Possible to get up-to-date data for large areas + Possible to react to information needs quickly + Possibility for accurate *in situ* observations + Time series exist – Costly – Some parameters (e.g. forest fragmentation) impossible or impractical to assess – Estimates of changes in rare classes not reliable	+ Produces information on landscape patterns – Most relevant parameters cannot be estimated or data reliability too poor for most information needs – Change estimates for small areas possible but unreliable – Local and regional estimates synthetic, and not necessarily unbiased	+ Produces information on landscape patterns + Change estimates for small areas possible – Some relevant parameters cannot be estimated or data reliability too poor for most information needs – Local and regional estimates synthetic, and not necessarily unbiased	+ Produces information on landscape patterns + Change estimates for small areas possible – Some relevant parameters cannot be estimated or data reliability too poor for most information needs – Local and regional estimates synthetic, and not necessarily unbiased	+ Produces information on landscape patterns – Some relevant parameters cannot be estimated or data reliability too poor for most information needs – Estimates are likely to be at least somewhat biased at all spatial scales – Estimation of reliability of the forest resources map not straightforward
(III) Harvest scheduling – timing of harvests	– Reliable data at stand level – Accuracy of the characteristics needed for decision-making – Critical information contents (in Sweden tree species-level map not produced)	– Does not produce data at stand level	– Reliability at stand-level poor	+ Estimates of growing stock are reliable at stand level + Possibility to assess spatial arrangement – Species identification, estimation of age, increment have high uncertainty	+ Estimates of growing stock are reliable at stand level + Possibility to assess spatial arrangement – Species identification, estimation of age, increment have high uncertainty	+ Estimates of growing stock are fairly reliable at stand level + Species identification, estimation of age, increment – Costly

(*Continued*)

Table 6. Continued.

Decision problem and specific examples	Critical properties of data for the task	Data acquisition methods Sampling-based field inventory (NFI)	Satellite images – Finland (MS-NFI) – Sweden (*k*-nn map) – Sweden (satellite data change detection)	3D point cloud from aerial photos – Norway (NFI)	ALS – Finland (separate management inventory) – Norway (separate management inventory) – Sweden (NFI)	Traditional FMI (visual assessment, aerial images) – Sweden – Norway – Finland (where ALS not yet available)
(IV) Promoting good practices in forest management – encouraging to tending of seedling stands – pre-commercial thinnings	– Reliable data at stand level – Timeliness	– Does not produce data at stand level	– Reliability at stand-level poor	– Species identification, estimation of age, increment have high uncertainty – Estimates of young/seedling stands have high uncertainty	– Species identification, estimation of age, increment have high uncertainty – Estimates of young/seedling stands have high uncertainty	+ Estimates of growing stock are fairly reliable at stand level + Species identification, estimation of age, increment – Costly
(V) Timber procurement planning (by forest industry) – buying timber from forest owners – fulfilling demand of mills	– Location of forest stands with immediate cutting potential – Suitable timber assortments – Timeliness, location	– Does not produce data at stand level	+ Timeliness – Reliability at stand-level not very good	+ Good reliability – Difficult and costly to achieve timeliness – Reliability of species-level data	+ Good reliability – Costly to achieve timeliness – Reliability of species-level data	+ Fairly good reliability at stand level + Species identification, estimation of age, increment – Costly
(VI) Operational planning of harvesting – harvest season selection: winter or summer – clustering harvests – selection of the mill to transport – optimal bucking – end use of the timber	– Accurate information on growing stock and it's quality – Specific site information needed at stand level, also in surroundings – Data need to be accurate at the time of harvesting: no need of accurate data in other time points	– Does not produce data at stand level	– Reliability at stand-level poor	+ Growing stock information sufficiently good for most purposes – Diameter distribution shape in different type of stands poorly distinguished – Estimates of timber quality currently not included	+ Growing stock data good – Diameter distribution shape in different type of stands poorly distinguished – Estimates of timber quality currently not included	+ Estimates of growing stock are fairly reliable at stand level + Species identification, estimation of age, increment – Costly
(VII) Investment planning – where to locate a mill? – sufficiency of timber resources for a planned mill	– Reliable long-term scenarios – Location of resources and potential – Timber assortments	+ Long-term forecasting of sample plot data is feasible – Spatial resolution can be too low for regional analyses	+ Full cover data + Reliable enough for resource estimation – Reliability for scenarios	+ Possibilities for full cover data exist – Timeliness can be an issue	+ Possibilities for full cover data exist – Timeliness may be an issue	– Regional estimates of unknown quality – Biased estimates

et al. 2014; Rahlf et al. 2014; Puliti et al. 2017; Tuominen et al. 2017). Ali-Sisto and Packalen (2017) noted that changes can be equally well detected from both image matching data and ALS data. 3D photogrammetric point clouds generally are much cheaper than ALS, but the actual difference in costs depends on local conditions.

Thus, the accuracy sufficient for decisions requiring localized information is the main benefit in the ALS applications. However, when the spatial scale of the campaigns increases, also the variation within the scanned areas increases. At a large scale, there will be variation in the quality of the product due to the scanning conditions (different days, leaf on/off) and multiple scanning sensors. The importance of such a variation needs to be addressed in the future. In the future, we also need to analyse if the combination of ALS and aerial photogrammetric point cloud data can be utilized to reduce these problems.

The utilization of, for example, denser ALS point clouds as well as multi-spectral ALS is also under research. In FMI, the benefits of denser ALS data may be utilized, for example, in the so-called edge-tree approach (Packalen et al. 2015). We expect that the sensor development of multi-spectral ALS instruments will improve the species separation. In the future, we need to analyse if the improvements are large enough for the needs of timber trade or for the planning of the end use of the timber.

Field data collection

Field data are required as training/modelling data used for mapping. The increased availability of large-scale 3D data sets can be viewed as the bridge to link the worlds of NFIs and FMI. One option is to use the NFI plot information as training plots in FMI either as the only source of field plots or in combination to the field plots specifically measured for FMI. This becomes possible, as increasing the area covered by ALS or aerial photographs will increase the number of NFI plots available for use in the map production. The need of not compromising the plot coordinates of permanent plots may hinder this usage, even though there are technical solutions to solve this problem.

RS pixel does not cover exactly the same trees as the field plot from the same point, especially when variable radius or concentric sample plots are used in NFI. This will also be reflected in the resulting models (e.g. Næsset et al. 2015). For instance, in the Danish case, only trees with dbh > 40 cm are measured in the full 15 m radius plot. On the other hand, Tomppo et al. (2016) compared the plot types for the FMI. They concluded that the plot type has only a minor effect on the accuracy of the results, and that the main source of uncertainty is the imperfect correlation between the RS data and the field plots. Similar results have also been obtained earlier (Maltamo et al. 2007, Maltamo, Packalen et al. 2009; Tuominen et al. 2014). However, the importance of plot types may depend on the prevailing forest structure and homogeneity. Location errors are an additional source of uncertainty in the models (Saarela et al. 2016).

One problem in the utilization of NFI plots is the distribution of plots, which is not designed for modelling purposes. For modelling purposes, a data set with as large variation in the explanatory variables as possible is advisable (Lappi 1993). A systematic sample is likely to include a large proportion of observations close to average, and only a few observations with extreme values. Therefore, a balanced set of plots from different types of forests is likely to form a better modelling data. However, it is not known how large an effect the plot selection (or resulting distribution) has for the accuracy (see, however, Grafström et al. 2014 for the effects of plot selection on model-assisted estimation).

In the Swedish and most recent Danish ALS-based maps using solely NFI plots, tree species proportions were not estimated (Nilsson et al. 2017). In Finland, the tree species proportions are estimated, but the accuracy is not as good as it used to be in traditional visual assessment. The same is true for the Norwegian dominant tree species maps (available for the Trøndelag region) based on NFI and image matching data. It can be assumed that total plot volumes can be estimated with a fairly low number of plots, but species-level results require more plots. For instance, Kallio et al. (2010) tested the effect of number of plots on the species-specific volumes. The accuracy of pine and deciduous species, which were minor tree species in the study, was improved up to 430 plots, which was the total number of the plots. However, for spruce, which was the main tree species, say, 200–300 plots were sufficient to reach optimal accuracy. Moreover, the properties of the tree species as such may have an effect on this. The number of field plots and the plot distribution may also have unknown combined effects on the accuracy.

In a recent test from Finland, a rather large inventory area (about 313,000 hectares) was considered (Savolainen 2016). The annual number of available forest NFI plots (131) was only 13% of the number of plots (including also sapling stands) which were measured by the Forestry Centre for the operative FMI. The effect of the NFI plots on the accuracy of total volume estimates was minor, but a larger effect is observed for species-specific estimates. Thus, increasing the use of NFI plots requires applying also plots measured in previous years, which introduces problems of temporal mismatch caused by, for example, thinning and clear-cut. Especially the thinned plots are not easily recognized, which may introduce bias. Also, the growth of stands will introduce uncertainty which increases with time. The magnitude of such uncertainty in the end product is yet unknown. The NFI plots also need to be precisely positioned using global navigation satellite system (GNSS), as the location errors might introduce variability into the estimates.

Once large data sets of auxiliary information (large geographical extent) are used, it may result in a lower accuracy of stand-level estimates compared to a local bottom-up process. This is due to the regional and local variation in calibrated model relationships caused by altitudal, latitudal, climatic, and site-specific differences in crown allometry and stand structures, as the plots are from a larger area; and inhomogeneous auxiliary data (Maltamo et al. 2016). Significant regional differences have been reported (Næsset and Gobakken 2008; Kotivuori et al. 2016; Nilsson et al. 2017), and even at the holding level, differences in crown allometry and stand structure have been shown to lead to biased estimators of up to 40% or more of the observed mean from one stand to the other (Næsset 2004). Not only will this reduce accuracy, but it will also lead to estimates that are too inaccurate for strategic and operational planning.

To mitigate this problem, several different options are available: (1) to use models that can be calibrated using local data such as kriging/mixed models where data are available (Räty et al. 2011; Räty and Kangas 2012), (2) to use geographically weighted regression (Zhang and Gove 2005), or (3) to use a spatial range when selecting the observations in non-parametric approaches like *k*-nn (Sironen et al. 2008). The relative efficiency of such approaches remains to be studied. It is possible to also account for the sensor effects in the models.

Estimating uncertainties

NFIs have a long tradition in statistical uncertainty assessment. Even though the sampling theory was not yet fully developed, the uncertainties were assessed also in the very first national inventories (Lindeberg 1924; Langsæter 1926). In the current NFIs, the design-based inference is utilized, where the selection of the plots forms the only source of uncertainty. While the sample design is systematic, estimators based on random sampling are used in Norway, Sweden, and Denmark (e.g. Fridman et al. 2014). These estimators give conservative estimates of the uncertainty. In Finland, a less conservative estimator utilizing a trend surface is assumed (Heikkinen 2006).

In FMIs, the accuracy assessment has been based on empirical estimates, e.g. from comparing the results to a more accurate inventory (Næsset 1991; Ståhl 1992; Haara and Korhonen 2004; Wallenius et al. 2012). Currently, the accuracy estimates concerning ALS inventories have been produced using techniques such as leave-one-out cross-validation for a raster cell level (Packalén and Maltamo 2007). The problem with the empirical estimates is that it is not necessarily possible to transfer the accuracy assessment from one area to another. This is also one of the reasons why multiple assessments have been conducted across all the Nordic countries (Næsset 2007).

It is recognized that providing uncertainty estimates on the stand level is useful also in FMIs. As the sample plots are not necessarily selected according to probabilistic principles, a model-based framework needs to be used. Model-based framework means that the randomness in the analysis comes from the model that describes the population, not from the selection of the sample plots (Kangas 2006). Then, uncertainties can be estimated using the model, even if the sample is purposively selected. In principle, model-based small-area estimators are applicable for stand-level inference. The problem is that there are very likely only one or in most cases zero plots available for a given stand, which results in synthetic estimators. It means that the results are based on a sample that is from neighbouring areas rather than the area of interest itself, and the resulting synthetic estimators are generally not unbiased due to unknown stand-level effects. While it is not possible to account for a potential stand-level effect in the point estimate (Breidenbach et al. 2015), several methods are available to consider stand-level effects in the estimate of the variance of a synthetic estimate (Magnussen et al. 2016). It is important to estimate the accuracy also if the FMI results are generalized to larger areas such as regions. Estimators of uncertainty at different scales would help in understanding the benefits and drawbacks of NFI and FMI estimates related to each other. The potential of both analytical and resampling estimators needs to be studied.

Methods such as data assimilation (Ehlers et al. 2013) could improve stand-level FMI estimates if taken to operational use. Data assimilation means that existing data can be combined with new data, in order to obtain more accurate estimates of the current situation. An additional benefit of these methods is that both Kalman filter and Bayesian techniques, commonly used for data assimilation, provide uncertainty estimates as part of the estimation framework (e.g. Varvia et al. 2017).

Decision-making perspective

When reflecting the data sets based on the specific decision problems, it was noted that in many cases, timeliness is a key criterion for the data. Especially in the monitoring of harvests and occurrence of natural hazards in forests, the timeliness is the most important issue (Table 6). Thus, satellite images are very important for such applications. When monitoring harvests, a satellite-based forest resources map that is produced every second year may not be timely enough. In some applications, more frequently available data such as raw satellite images must be utilized, as is the case in Sweden (Olsson 2015). On the other hand, if the removed volume or biomass is of interest, then satellite images as such are not enough. For example, in Denmark, declaration of wind-throw events and the activation of insurance payments are based on an assessment of the severity of the event, requiring that minimum one-year harvest of a region must be affected. Both airborne and space radar data are used for assessing changes in relation to wind throw (e.g. Fransson et al. 2002; Ulander et al. 2005; Tøttrup et al. 2014).

Practically real-time data for updating harvested area can be obtained from data collected with harvesters, if the data can be automatically processed. This approach is currently being tested in Finland, Norway, and Sweden. As it may be difficult to get all harvester drivers to collect this information, unless the data collection is completely automatic and does not require investments in equipment, a satellite image-based approach will still be required. Even though it is difficult (or impossible) to see thinned stands from a satellite image, delineating the thinned area from a harvester data can be equally uncertain: locating accurately where the harvester has moved is not enough to accurately locate the stand borders.

When monitoring the sustainability of the forest management, large-scale sample-based results are useful for many indicators, but a timely forest resources map is needed to assess changes e.g. in the spatial configuration of the landscapes (Table 6). This does not necessarily require wall-to-wall maps, as the changes can be analysed using a sample of landscapes (Ståhl, Allard et al. 2011). On the other hand, in monitoring of more subtle changes like forest growth

(McRoberts et al. 2015) or land-use changes, sample information can be used at the regional level. On the local level, 3D RS information or field data are needed to obtain accurate results. With small areas and short inventory intervals, RS material sufficiently accurate to detect small changes is not yet available.

In most forest inventory studies, the interest has been on the accuracy of the above-ground volume or biomass estimates. It should nevertheless be noted that even though volume has been a main variable of interest, it has been understood by all parties (the inventory provider and the forest owner) that multiple additional variables are needed for the management planning, which is the major objective of the FMI to support. These additional variables differ somewhat between the different countries depending on data needs for the various decision support tools in use. In the future, also the benefits related to these other variables should be assessed, to direct the future efforts in the development of data acquisition processes.

There are currently only three ways to produce sufficiently accurate FMI information for counselling and decision-making of the forest owners (Table 6):

(1) old style stand-wise field work aided by interpretation of orthophotos and now also lidar products;
(2) interpretation of aerial photos in photogrammetric work stations;
(3) ALS (which, however, does not yet provide reliable tree species data).

The traditional field work and photo interpretation are steadily decreasing in favour of ALS. In laser scanning, variations between the different campaigns (different quality ALS data) have resulted in an unacceptable quality variation of produced forest resources data (Packalen, P., pers. comm. 2017). This will likely reduce when the campaigns get more standardized. The photogrammetric point cloud data are another possibility, but it is not tested enough in an operational scale yet.

It is possible that any 3D data acquired by airborne sensors will produce sufficiently accurate information also concerning logistics and wood procurement (Table 6). The needs for improved accuracy can be found, especially in young stands, which have not been included in the practical ALS-based FMI e.g. in Finland. However, the topic is under active research (Næsset and Bjerknes 2001; Korpela et al. 2008; Korhonen et al. 2013; Ørka et al. 2016). Diameter distribution information does not have a high value for non-industrial private forest owners in the harvest decisions (Saad et al. 2015), but it can have high value in price negotiations. For that purpose, the current level of accuracy can be good enough. In logistics and wood procurement, the information on soil, water, and snow conditions could be equally important as the actual forest resource data.

The possibilities for improvement of the end product value of the harvested trees by better selection of raw material are potentially high. For instance, an accurate estimate of diameter distribution may have a very high value for companies making decisions on where each batch of timber is optimally used. Existing RS-based species-specific diameter distribution studies (e.g. Packalén and Maltamo 2008; Peuhkurinen et al. 2008) have shown that the current level of accuracy may not be adequate for these purposes, at least not for minor tree species. An obvious way to improve diameter distribution estimates would be to first improve the species classification. This might be done by technological developments such as higher density ALS, and multi-spectral or hyper-spectral sensors.

Other important variables for improving the end product value in timber industry are the quality of the stem and branchiness of the trees. Information on the usefulness of 3D information (ALS or photogrammetric point cloud data) in estimating the quality is still largely missing (see, however, Maltamo, Peuhkurinen et al. 2009, 2010; Bollandsås et al. 2011). Quality information is available from terrestrial laser scanning (e.g. Kankare et al. 2014) and in less detail from field measurements, but it is not clear if and how this information can be generalized to a larger scale.

Traditionally, regional assessments of forest resources have been carried out using sample-based data, but in the future, it may be possible to utilize wall-to-wall maps for such analyses. For instance, in Finland, the Forestry Centre assesses questions such as the amount of hectares needing tending based on the FMI data. The benefit of using a forest resources map for regional analyses is that also, for example, the distances to the mills from stands potentially harvested can be calculated. However, if the FMI information is a combination of several measurement campaigns that may or may not cover the whole region, with varying conditions and sensors, there is a possibility of bias in the aggregated estimates. Moreover, there is a serious challenge in assessing the uncertainties of such estimates. The risks related to using FMI information in regional analyses need to be assessed in the future.

Ownership of the data

In Finland, the government budget covers the production of pixel- and stand-level data. In the future, the data will be freely available also to users other than forest owners. This has been seen as a threat to traditional holding-level forest planning, as the added value of the management plan may be low compared to the costs of such a plan. This concerns especially Finland, where the freely available data also include recommendations of the treatments in the short run. In Sweden, a similar discussion has been going on. There, the ALS-based forest resources map is already freely available. In Denmark, the laser scanning-based forest resources map has been freely available, but yet, the forest planning is based on the traditional data acquisition methods.

However, the service providers working in the forest sector have developed new business models and offer services based on the new data source, for example, by complementing the map with their own data in a profitable manner. One example is a service provider that offers updating of forest maps, based on the free laser scanner-based estimates in combination with more recent 3D data from digital photogrammetry. In Finland, UPM-Kymmene Ltd has published an application based on Finnish multi-source inventory data for estimating the value of a forest holding. This service is available to all. The ALS-based forest resources map produced by the Forestry Centre have been used as a basis for a similar service by OP Bank and Stora Enso Ltd in Finland, but these services are at the moment only available for the owner of the holding and naturally only for those regions where the Forestry Centre has completed the ALS-based FMI. Thus, the free data may reduce some of the current business opportunities, but it may also help in inventing new opportunities.

One argument for giving free access to the data has been the assumption that open data may promote the timber sales and bioeconomy in general. There is no research to our knowledge that documents this notion. However, the demand of timber mostly depends on the demand of forest products, and it may be difficult to separate the effect of open data, unless comparisons between countries with different policies can be made.

In general, services such as forest resource maps that are completely based on public data should remain public data. EU directives also recommend the reuse of publicly collected data as much as possible (Directive 2003/98/EC revised by Directive 2013/37/EU). However, requiring that maps that are partly based on public data should also remain public can be disastrous for the business models of the private companies. On the other hand, it is a natural development for publicly funded institutions providing forest statistics to improve their estimates by combining all available data sources.

Roadmap for the future development

Large-scale RS information may change the roles of NFI and FMI from completely independent processes to processes with possible synergies. In the future, RS material will be more and more utilized in NFIs as auxiliary information, in defining the design, estimation, and inference. The methods to analyse data have also been developing fast. In FMI, the methodological developments might facilitate improved precision at reduced costs.

For regional and national decision-making, sample-based data are suitable, but for several decision problems, wall-to-wall forest resources data are required. Even though the cost-efficiency of full cover forest resources data acquisition can be improved through the synergies of these two systems, there are also obvious challenges. For instance, while there is plenty of evidence that using NFI plots as training data instead of specifically selected set can produce accurate enough estimates of the main features such as total volume, it is unclear if using solely NFI plots as ground reference can produce accurate enough information for the decisions where e.g. species-level or assortments-level information at the stand level is needed. The usefulness of NFI plots for these purposes can be increased by selecting the plots, at least partly, based on auxiliary variables to make the data more suitable for modelling purposes.

For regional and national decision-making, the accuracy of sample-based data is usually sufficient. The smaller the unit of decision-making, the more challenging it is to produce data with sufficient accuracy (using a fixed set of sample plots). In this situation, it is important to analyse which variables are critical in decision-making, and develop the methodology to provide sufficiently accurate information concerning these variables at the required spatial scale (Corona 2010, 2016). In addition to the basic characteristics such as volume and basal area, the benefits obtainable from improving the accuracy of characteristics such as species proportions, quality or soil conditions at grid cell and stand level need to be quantified. The need for accurate information from such variables obviously depends on the decisions to be made based on the data. It is also important to analyse the importance of the timeliness of the results, i.e. what should be the interval between the maps produced.

While the cost-plus-loss analyses carried out so far have provided evidence that with laser scanning-based forest information, clearly, better decisions can be made than with the traditional visual FMI methods (e.g. Eid et al. 2004), it is not clear if e.g. the markedly cheaper 3D aerial photogrammetric data will allow the same. These benefits obtainable with a given RS material are also related to the collection of the field data and modelling methodology used to estimate the forest resources.

New, developing technology can in the future improve the accuracy of forest resources information. For instance, availability of high-density and multiple-channel ALS data is increasing, which is likely to improve the species recognition. In addition, it is possible to improve the timeliness of the data, when larger areas can be covered each year. Thus, hopefully, these new technologies will also improve the cost efficiency of forest data acquisition. However, there are challenges also in improving the cost efficiency. As the area being covered annually by laser scanning or aerial photogrammetric 3D data increases, it will introduce variation both in the forest characteristics and in the equipment used and conditions met, i.e. in the quality of the produced point clouds. The availability of the equipment may also be a challenge. These questions, again, are related to the plots available as reference plots, their configuration and size, the location accuracy, and also their measurement time compared to the collection of the RS material. There are obvious synergies between the NFI and FMI available in the large-scale estimation methodology and technology: the larger the areas involved, the more the NFI and FMI needs may coincide.

NFI data have typically been published with information concerning the accuracy. The accuracy assessments are based on sampling theory, while the FMI data have typically been published without accuracy assessment (except for specific test cases). However, the smaller the areas in question are from an NFI perspective, the more NFIs and FMIs have in common also in the methodology, for instance, the small-area estimation methodology can be used for estimation of accuracy also in FMI. Thus, very important synergies between the two inventory types may be achievable in the method development.

Mapping biological diversity has also received some interest. The role of RS for mapping of ecosystem services is likely to increase also in other Nordic countries (Vauhkonen and Ruotsalainen 2017). Many important forest variables are not correlated to RS data so that there are also clear limitations that require more research before recommendations on practical use can be given.

As our conclusion, we present the most important research questions emerging from the analysis. We propose that a common research programme for the Nordic countries is launched to solve these problems:

(1) Cost-plus-loss analysis of the different strategies of producing FMI data from the perspectives of different potential users of the data. The strategies that require further attention are e.g. ALS and local plots, ALS and NFI plots, image matching and local plots, and image matching and NFI plots. It is important to be able to detect the variables that are critical for the decision-making, and where the future methodological improvements are needed.
(2) Possibilities for improving the accuracy and reducing the costs of the data provided by FMI and NFI using new technologies, for instance, by more intensive use of NFI plots for large-scale campaigns with 3D materials in addition to plots specifically selected for the FMI purposes. The problems related e.g. to within-region variability of forest characteristics, sensor, and weather condition variability in large-scale campaigns and availability of recently measured NFI plots need to be addressed.
(3) Possibilities of aggregating model-based raster cell-level estimates for larger areas, from the stand level to the region level. The problems in estimating the uncertainty involved and the possibility of bias and its significance in decision-making are of importance. The usefulness of model-based and sample reuse methods and assessing the uncertainties need to be addressed.
(4) Possibilities of improving the information content of the forest resources maps with quality information such as branchiness or occurrence of root rot. The main question is if map products of these variables are sufficiently accurate for decision-making.
(5) Possibilities of utilizing 3D material from several sources such as image matching and ALS, or from several points in time using data fusion. The important question here is if data fusion will provide sufficiently accurate forest information to lengthen the inventory interval to obtain cost savings due to reduced field work. Cost-plus-loss analysis of data fusion compared to a new inventory is needed.
(6) Possibilities for using wall-to-wall maps for change monitoring and producing the accuracy assessments for the changes. The main question is to address the scales of changes that can be accurately assessed from different types of forest resources map time series. At the regional or municipality level, the map could be used in post-stratification or model-assisted estimation of change, but at smaller scales (stand or pixel level), fully model-based approach is needed.

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