Remote Sensing of Environment 174 (2016) 279–289

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Review

A questionnaire-based review of the operational use of remotely sensed data by national forest inventories

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 13 August 2015
Accepted 28 August 2015
Available online xxxx

Keywords:
COST action FP1001
Case studies
Satellite imagery
Spaceborne data
Aerial photography

ABSTRACT

We report on the operational use of remotely sensed data by national forest inventory (NFI) programmes in 45 countries representing approximately 65% of the world's forest area. The analysis is based on responses to a questionnaire prepared under the auspices of COST Action FP1001 “Improving Data and Information on the Potential Supply of Wood Resources: A European Approach from Multisource National Forest Inventories (USEWOOD)”. Responses were received from NFI remote sensing experts from both European and non-European countries. Three major conclusions were drawn from the study: (1) remote sensing now plays an essential role in many NFI programmes and provides data that can be used to enhance estimates for the most meaningful and commonly reported forest resource parameters; (2) a wide spectrum of remote sensing methods are currently used by NFI teams; and (3) although substantial effort and attention has been focused on the use of aerial photography and spaceborne sensor data for mapping and enhancing estimation, integration of uncertainly estimation requires additional attention.

The operational use of remotely sensed data by NFI programmes is illustrated for three case studies: a case study for Switzerland focuses on digital aerial photography, a case study for Finland focuses on spaceborne sensor data for small area estimation, and a case study for the USA focuses on spaceborne sensor data for increasing the precision of large area estimates. Although use of remotely sensed data by NFI programmes may remain region-specific and some approaches are not readily transferable, generally applicable good practice guidelines were formulated on the basis of the questionnaire responses and the case studies. These guidelines are intended to promote better use of limited financial resources and to increase the accuracy and precision of NFI estimates.

Published by Elsevier Inc.

Contents

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http://dx.doi.org/10.1016/j.rse.2015.08.029
0034-4257/Published by Elsevier Inc.

1. Introduction

Capitalizing on development work spanning several decades and in some cases more than 100 years, technologically advanced national forest inventory (NFI) programmes using statistical sampling have been established in many European and non-European countries (Tomppo, Haakana, Katila, & Peräsaari, 2008; Tomppo, Olsson, et al., 2008, Tomppo et al., 2011; Lawrence, McRoberts, Tomppo, Gschwantner, & Gabler, 2010). The earliest NFIs were established in the Nordic countries and the United States of America (USA) and focused on the continued availability and supply of timber with an emphasis on acquiring information related to forest area, volume and growing stock increment (LaBau, Bones, Kingsley, Lund, & Smith, 2007; Tomppo, Haakana, et al., 2008, Tomppo, Olsson, et al., 2008, Tomppo et al., 2011). Later, NFI programmes introduced new variables and new sample designs to estimate non-timber attributes related to biodiversity (e.g., naturalness, forest structure, deadwood volume) and forest health (e.g., crown vitality, defoliation) (Tomppo, Gschwantner, Lawrence, & McRoberts, 2010, NFI Report Chapters 1–37).

NFI plot-based, in situ surveys integrated with aerial photography and spaceborne sensor data both serve the requirement for ever more diverse and detailed forest statistics and produce relevant spatially explicit products. Remotely sensed data have been incorporated into operational forest inventories, and estimates enhanced through the use of remote sensing-based maps can now be expressed in forms similar to sample-based estimates. McRoberts and Tomppo (2007) list four primary ways by which remote sensing approaches enhance NFIs: (1) providing faster and less expensive methods for estimating forest attributes; (2) increasing the accuracy of large area inventory estimates, often via stratified or weighted estimation; (3) providing inventory estimates with acceptable bias and precision for small areas for which sufficient field data are not available; and (4) producing forest thematic maps that can be used for purposes such as timber production, procurement, and ecological studies.

Historically, interpretation and mapping of trees and stands based on aerial photography have represented the most popular form of remote sensing of forests (Spurr, 1960). Aerial photography is the oldest and most frequently used form of remote sensing and was first used to aid stratification during the 1940s and 1950s by the Forest Inventory and Analysis (FIA) programme of the U.S. Forest Service (Bickford, 1952; LaBau et al., 2007) and by Spain and Switzerland in the 1960s and late 1970s, respectively (Martinez & Condes, 1997; Brassel & Lischke, 2001). The increasing availability of aerial photography in digital formats and the ease of integration with auxiliary and other GIS data has greatly facilitated its use (McRoberts & Tomppo, 2007). From an operational perspective, considerable cost savings may be realised by initially observing NFI plot locations using aerial photography or high resolution satellite photography.

NFI country reports (Tomppo et al., 2010) and other surveys (Köhl & Päivinen, 1996) indicate that aerial photography continues to be widely used by European NFI programmes. Koch (2013) identifies multiple reasons for continued use of aerial photography: (1) long tradition; (2) fine spatial resolution;(3) greater probability of acquiring cloud free data within a specific time window; (4) close cooperation between survey institutes acquiring photography and forest authorities; (5) relatively large costs for very high resolution satellite data; and (6) the relative ease of capturing smaller European survey areas using aerial photography when compared to larger non-European countries such as the USA, Canada, or in South America.

In countries outside Europe, NFI use of earth observation data from satellites is more common (Lawrence et al., 2010; FAO, 2008; Koch, 2013). The integration of remotely sensed satellite data with field inventory data for the estimation of forest parameters dates back to the 1980s (e.g. Poso, Hame, & Paananen, 1984; Halme & Tomppo, 1987; Danson, 1987; Tomppo, 1988). Techniques such as the k-nearest neighbours (k-NN) method were subsequently refined and further developed for regional applications in the USA (Franco-Lopez, Ek, & Bauer, 2001; McRoberts, Nelson, & Wendt, 2002a) and operationally at national scales in Finland and Sweden in the 1990s and 2000s (Reese et al., 2003; Tomppo, Haakana, et al., 2008). The opening of the Landsat archive, making the entire historical time series of data freely available, greatly facilitated the use of satellite imagery (Loveland & Hansen, 2012). Satellite-based methods were first implemented operationally as part of the Finnish multi-source NFI (MS-NFI) by Tomppo in the early 1990s (Tomppo, 1991; Tomppo et al., 2011). Similar approaches to those in Finland and the USA for integrating NFI and field plot data with Landsat data have been tested in Norway (Gjertsen, 2007), Ireland (McInerney, Pekkarinen, & Haakana, 2005), Austria (Koukal, Suppan, & Schneider, 2007), Italy (Maselli, Chirici, Bottai, Corona, & Marchetti, 2005) and Brazil (Vibrans, McRoberts, Moser, & Nicoletti, 2013).

Other earth observation systems, such as synthetic aperture radar (SAR) or polarimetric SAR interferometry (Praks, Kugler, Papathanassiou, Hajnsek, & Hallikainen, 2007; Hajnsek, Kugler, Seungkuk, & Papathanassiou, 2009) have been tested and used to estimate forest variables over large areas. In particular, the use of airborne laser scanning (ALS) data in combination with NFI plot information has increased in recent years and has been shown to be effective for enhancing the estimation of forest inventory attributes (Naesset, 2007; Vastaranta et al., 2013; Wulder et al., 2013; McRoberts, Næsset, & Gobakken, 2013). Although data from these sensors have yet to be used operationally for national-level strategic assessments by NFIs, they are used operationally for stand-level forest management inventories in Finland, Norway and Sweden.

Despite the increasing operational use of remotely sensed data by NFIs, practical information on the detail, scale and approaches used has not been readily available in a consistent format. Therefore, one of the overall objectives of COST Action FP1001 “Improving Data and Information on the Potential Supply of Wood Resources” was to provide such information. COST (European Cooperation on Science and Technology) is a European framework for promoting and facilitating scientific cooperation among European scientists and researchers (COST, 2014). COST Action FP1001 focused on European approaches for using MS-NFI data to improve information on the potential supply of wood resources (COST FP1001, 2014). The specific objectives of the study reported herein were threefold: (1) to summarise information on the operational use of remotely sensed data by both European and non-European countries via responses to a questionnaire survey; (2) to illustrate state-of-the-art remote sensing support for NFIs via case studies; and (3) to provide good practice guidelines for use of remotely sensed data by NFIs based on responses to the questionnaire and the case studies.

2. Materials and methods

A review, assessment and classification of remote sensing methods as used operationally in NFIs was conducted by evaluating 37 NFI country reports in Tomppo et al. (2010) and relevant surveys, reports and publications (Köhl & Päivinen, 1996; Westinga, Bijker, & van Dijk, 1999; Köhl, Magnussen, & Marchetti, 2006; McRoberts & Tomppo, 2007; FAO, 2008; McRoberts, Tomppo, & Næsset, 2010; Koch, 2013). A 65-question survey was designed following review of NFI remote sensing methods and suggestions from participants in Working Group 2 (WG2) of COST Action FP1001. The questionnaire was modified and enhanced based on feedback from collaborating WG2 members and included seven thematic areas:

(1) personal, organisational data related to the national expert or respondent;
(2) basic information related to the NFI, forest resource assessment of interest;
(3) use of aerial photography and associated technologies;
(4) use of spaceborne remotely sensed data and associated technologies;
(5) forest attribute maps and derived spatial products generated from NFI data with the support of remotely sensed data and technologies;
(6) remote sensing software and systems, technical expertise and personnel;
(7) current and future development prospects for remote sensing in NFIs.

The questionnaire was distributed to WG2 country representatives in 2011 with further follow up to individual countries for updates and/or clarifications in 2012 and 2013. In addition, national experts outside the participating COST Action FP1001 countries were contacted to contribute to a more complete global picture of remote sensing use by NFIs.

To illustrate the operational use of remote sensing in NFIs we analysed descriptions of the state-of-the-art for three countries: (1) use of digital aerial photography in Switzerland; (2) use of satellite imagery for small area estimation in Finland; and (3) use of satellite imagery to increase the precision of large area estimates in the USA. Finally, good practice guidelines for the implementation of remote sensing by NFIs were formulated based on the assessment and analysis of the questionnaire responses and the case studies.

3. Results and discussion

3.1. General results

This study was conducted as a questionnaire survey, with questionnaires submitted to relevant NFI remote sensing experts. Initial drafts of the remote sensing questionnaire were developed, circulated for review by a small group of COST Action members, and subsequently revised. As with previous COST Action surveys of this nature, the results depend on multiple factors: (1) the sampling approach; (2) the influence of non-responses; and (3) the potential of the respondents to correctly answer the questions (Cienciala et al., 2008; Winter, Chirici, McRoberts, Hauk, & Tomppo, 2008). Although the internal review of the questionnaire likely circumvented serious misinterpretations, some data quality problems still occurred such as obvious logic errors or responses inconsistent with other published material relating to a particular country's responses (e.g. Lawrence et al., 2010). In obvious cases these misinterpretations were excluded from the results and treated as missing values; alternatively, respondents were contacted for clarifications and corrections. The questionnaire responses were analysed by assessing the proportions of particular responses to individual questions.

Of the 48 countries contacted (Fig. 1), 43 responded fully, two responded partially, and only three failed to respond. Based on the FRA 2010 report and forest definitions used by the responding countries, the forest area of the responding countries represented 65% of the global forest area (FAO, 2010). This estimate includes 99% of the total forest area of the 28 European Union (EU) countries plus Iceland, Norway and Switzerland (FAO, 2010). Apart from Croatia and Serbia, the responses provided a complete overview of the operational use of remote sensing by European NFIs.

3.2. Summary of organisational information for questionnaire respondents

The analysis summarised responses to questions regarding the respondents' organisations as well as basic information pertaining to their NFIs such as sampling designs, and then focused in more detail on the description and operational use of remotely sensed data.

Most countries responding to the survey have completed or are in the process of completing at least one complete national inventory. To date, Finland is conducting its 12th inventory, and Norway is conducting its 10th inventory. Approximately 98% of the questionnaire respondents indicated that their organisations operate at national, sub-national or local levels, with the vast majority (93%) indicating that they represented governmental agencies. Approximately 78% of respondents indicated that their NFI programmes operate in Temperate ecological zones, with 24% of respondents indicating that their programmes also operate within Boreal zones. One country, the USA, operates across Temperate, Boreal and Tropical (wet, dry) ecological zones. Based on the questionnaire responses, 93% of countries conduct a sample-based statistical inventory with temporary or permanent sample plots or points located on a grid or tessellation of space. Five countries (11% of respondents) aggregate stand-level information for their assessment in addition to a statistical sample-based approach.

3.3. Overview of the use of remotely sensed earth observation data by NFIs

Approximately 71%, or 32 of the 45 countries, consider their NFIs to be dependent or partially dependent on earth observation data (Fig. 2). Approximately 31% of respondents (14 countries) considered aerial photography indispensable for the completion of their NFI, whereas satellite images were considered as essential by only 13% and a combination of both satellite images and aerial photos by 9% of respondents. A further 56% of respondents considered their NFIs not to be dependent on spaceborne sensors or data, whereas 33% considered their NFIs not to be dependent on aerial photography. No country indicated operational use of or reliance on data from radar or lidar sensors or unmanned aerial vehicles.

Approximately 29% of respondents consider aerial photography to be at least partially essential and 27% of respondents consider satellite images to be partially essential for assisting forest area estimation, facilitating field work, validating NFI results or assisting with other operational aspects of their NFI programmes. Approximately 7% of respondents indicated that local, regional or sub-regional forest parameters cannot be estimated without aerial photography and/or satellite imagery.

Remote sensing applications within NFIs are manifold. Construction of forest attribute maps is the most common application reported by responding countries (38% or 17 countries). A further 27% or 12 countries, conduct double- or multi-phase sampling for stratification using a combination of aerial photography, satellite imagery and other auxiliary spatial data such as topographic, land cover/use, and land ownership maps. The primary use of aerial photography relates to plot-level evaluations such as assessing forest cover, aiding stratification, facilitating field access, and navigation (Section 3.4.2).

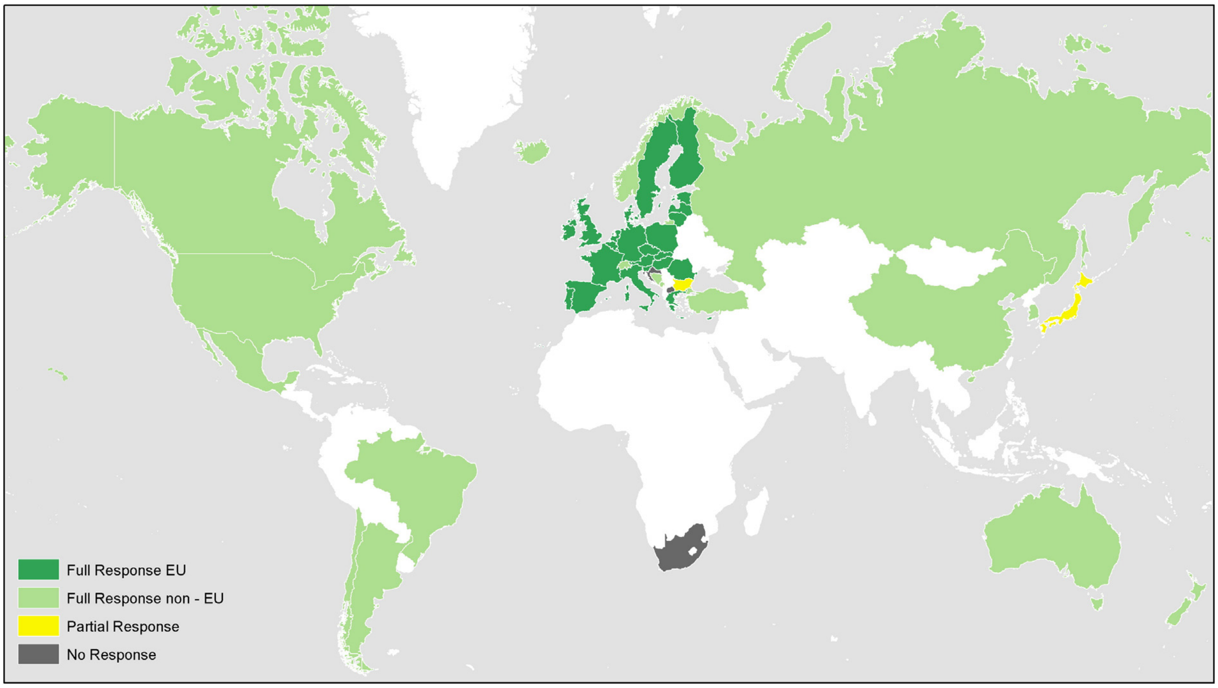

Fig. 1. Countries invited to submit responses to the National Forest Inventory remote sensing questionnaire.

Approximately 65% of the respondents (30 countries) construct map products by combining their NFI data and satellite imagery, aerial photography, or both. The map themes include forest cover and or area (57%), forest type (57%), land cover type (41%), species groups (28%), biomass (15%), and volume of growing stock by tree species or tree species groups (20%). Maps of forest attributes such as basal area, stem density, age, height, mean diameter, forest productivity, and fertility are constructed by fewer than 10% of the responding NFI programmes.

The relative importance of satellite and aerial photography is reflected in the time devoted to remote sensing and photogrammetric activities. The NFI programmes of 40% of respondents or 18 countries commit at least one month per year to these types of analyses. The NFIs of approximately 49% or 22 countries use outside agencies and or third party research institutes for remote sensing or photogrammetry services that include image processing, image classification, statistical analysis, computer programming, and modelling; 33% or 15 countries conduct these analyses in-house. Only 26% or 12 countries indicate that the technologies, methods and processes for use with remote sensing and or photogrammetry can be readily applied or transferred to other organisations or NFI programmes.

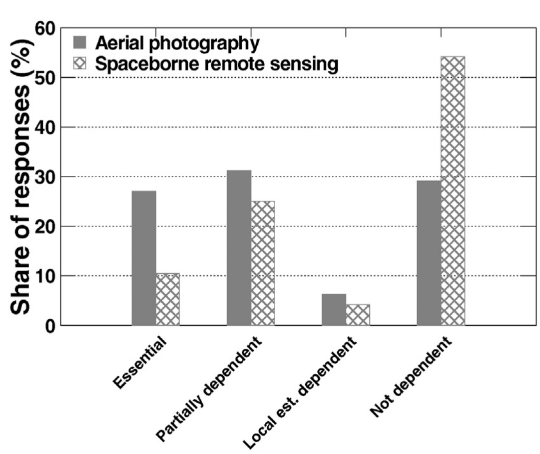

Fig. 2. Dependency on the use of aerial and/or satellite images to complete NFI tasks.

Finally, four countries use aerial photograph as auxiliary information to enhance estimation of parameters for small areas with few field plots. Two countries use satellite images to enhance these small area statistical estimates, and two countries use both aerial and satellite imagery for this purpose. Post-stratified estimation using map products based on satellite images and field plot data is used to enhance the estimates by five countries (11% of the respondents).

3.4. Use of aerial photography to support NFIs

3.4.1. Sensor specification and spatial resolution

In some cases, the names or terms adopted in the questionnaire for sensor specification (e.g., film type, colour, RGB) and sensor type (most countries currently use digital sensors) appear to have been confusing to or misinterpreted by respondents. Thus, the following analysis is based on three assumptions regarding questionnaire responses.

Firstly, for countries using aerial photography operationally, we assume that digital sensors are used because they are widely available and almost exclusively used currently in aerial photography acquisition programmes. Some exceptions may arise in cases where a country still uses analogue frame cameras. Thus, the large numbers of “Not Applicable” (18 countries) responses related to aerial photography film type and the “Not Applicable” (14 countries) responses related to the camera or sensor type question are most likely due to the fact that digital sensors are used. Furthermore, it appears that the question related to aerial film type (e.g., colour film versus colour infrared film) was answered in the context of current use of digital (stereo) orthophotos and digital multi-spectral sensors.

Secondly, the spatial resolution of aerial photography used by some countries appears to be rather coarse. Digital sensors with spatial resolution of less than 100–200 cm is used by five countries. This type of aerial photography is most likely acquired in combination with finer resolution imagery from the same sensor. Countries with relatively large areas use specific flight heights (high altitudes) with commercially available airborne sensors to generate or update topographic maps.

Thirdly, most countries responding use either digital orthophotograph (28 countries) or digital stereo-images. Both types of aerial photography formats are combined with auxiliary equipment (e.g., 3D computer screens using polarized eyeglasses) or are used in combination with photogrammetry, remote sensing or GIS software and systems. Paper-based formats such as hard copy aerial photographs or aerial photography film stocks or both are currently used by only three NFI programmes. A total of five countries use both digital and analogue aerial photographic imagery types simultaneously in their NFI programmes.

3.4.2. Questionnaire responses

In general, aerial photographs are acquired by national mapping, topographic, cartographic or forest agencies and seldom specifically by an NFI programme or a third party image provider. The overall dependency on the use of aerial photograph to complete NFI tasks is summarised in Fig. 2.

The primary use of aerial photography by NFIs relates to plot-level assessments. These assessments include determining if plot locations are on forest land (67%), facilitating access or navigation to field plots (56%), and improving forest area estimation based on forest/non-forest stratifications (44%). In 25% of the NFI programmes aerial photography is also used to define or redefine forest types (22%), to assess forest condition for inaccessible plots (20%), to delineate stand boundaries (20%), to map Other Wooded Land (OWL) or Trees Outside Forest (TOF) (20%), to map disturbed areas (18%), to update forest maps between inventory cycles (18%), and to assess other plot-level parameters such as tree density and height (16%).

Based on questionnaire responses, as many as 12 types of attributes are collected from aerial photo plots. In this phase, plots are not actually surveyed in the field, but rather information is collected from aerial photography which serves as a surrogate for field observation. The most frequently assessed attributes are forest/non-forest land use (51%), forest type (31%), and dominant tree species (22%). More specific stand variables such as height, health, crown diameters, regeneration, and stand edge/shape metrics are less frequently assessed (<11%), with the exception of crown cover (24%) and development stage (16%).

TOF and OWL are land use categories that do not satisfy FAO's definition of forest (de Foresta et al., 2013). For this questionnaire, OWL was defined to include individual trees, parkland, rows of trees, hedgerows and woody linear features. Overall, 24% (11 countries) of respondents collect information on TOF and/or OWL using aerial photography, whereas 44% of respondents indicate that their NFI programmes do not collect this type of information.

Aerial photograph have been used operationally in NFIs for many years (Fig. 3). Whereas 18% of respondents have been using aerial photographs for more than 40 years; 20% of respondents began using aerial photography operationally in their NFIs in the last 5–10 years; and approximately 13% of respondents began using aerial photography only in the last five years. Approximately 9% of respondents indicated that their NFIs used aerial photography in the past but switched to satellite imagery or other data sources.

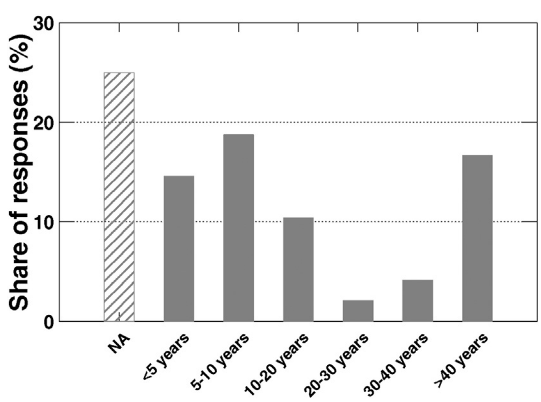

Fig. 3. Time span of operational usage of aerial photographs within an NFI programme.

3.5. Use of satellite images to support NFIs

3.5.1. Satellite sensor specification and spatial resolution

The most frequently used satellite systems are medium-resolution satellites: Landsat TM and ETM (13 countries), followed by SPOT 1-5, HR VIR, HRG (9 countries), and IRS (2 countries). In many countries different satellite sensors have been used simultaneously or for clarification and refinement. Fine resolution satellite imagery such as provided by Quickbird, WorldView 1 and 2 or GeoEye 1, is used by only four NFI programmes. Additional spaceborne sensors reported include DMC, MODIS, ALOS, ASTER, SAC-C and RapidEye.

Of the respondents using satellite images, 40% or 18 countries, use satellite data at a national scale with wall-to-wall data coverage. A total of 17% (8 countries) of respondents use satellite imagery at sub-national levels or scales. Satellite imagery is often used in combination with auxiliary digital maps, in particular land cover and or land use maps (41%), topographic maps (30%), digital elevation models (28%), and administrative boundary data (24%) and less so with climatic, ecological, geological, hydrological and soil or land ownership category maps. Approximately 13% use satellite images to facilitate the assessment of TOF and OWL. A further 45% of respondents indicate that their NFIs do not collect TOF or OWL information using satellite images.

Finland reported the longest operational use of satellite data, having used this technology since the late 1980s. Approximately 17% or 8 countries responding to the survey have been using satellite imagery for the last 10–20 years, five (11%) countries for 5–10 years, and eight (17%) countries for fewer than five years.

The primary methods used to extract information from satellite images incorporate either prediction and estimation based on image analysis using field data (31% of respondents or 14 countries) or visual interpretation and expert knowledge (13% of respondents or six countries). In Canada, satellite imagery is primarily used to conduct automated image segmentation with subsequent human interpretation of the segmented image. Many estimation techniques are used including supervised parametric (maximum likelihood, discriminant analysis, and linear, nonlinear, and logistic regression) (eight countries) and non-parametric approaches (k-NN), and unsupervised approaches (neural networks, isodata or k-means) (seven countries). Other methods include binary decision trees, fuzzy logic, and object-based image analysis.

3.5.2. Questionnaire responses

A total of 13 countries or 29% of respondents indicate that their NFIs use auxiliary spatial databases to enhance map products constructed using satellite imagery. The most commonly used forms of digital map data used in combination with satellite imagery are land cover/land use maps (41% or 19 countries), topographic maps (30% or 14 countries), digital elevation models (28% or 13 countries) and administrative boundary data (24% or 11 countries). Digital map data comprising ownership data, ecological regions, soils or geological data are also used in combination with satellite data. A total of seven countries (16%) use segmentation techniques to enhance map products. The most commonly produced attribute or thematic maps estimated using remote sensing methods and data from NFI programmes are forest cover or forest area maps (58% or 26 countries), forest cover type maps (58% or 26 countries), land cover type maps (42% or 19 countries), and species groups maps (29% or 13 countries). Biomass, volume, basal area and height are other themes mapped by NFI programmes using remotely sensed data and associated technologies.

Eight countries or 17% of respondents have used NFI map products constructed using remotely sensed data and technologies to investigate current or past NFI sample designs with a view to introducing efficiencies such as enhanced stratification for variance reduction, stratum size estimation, reduction of field sample sizes and cost savings. Ten countries (22%) indicated that map products constructed by their NFI programmes serve as input data or validation data for other national land cover map products.

Nine (20%) countries indicated that map products constructed by their NFIs currently are used in combination with auxiliary spatial data such as administrative data/boundaries to calculate local or small area estimates or map products of forest variables (e.g., volume, height, basal area by administrative unit) where sufficient field data are not available. Furthermore, only 12 countries (26%) indicated attempts to include estimation of uncertainty for parameters estimated from NFI remote sensing-based map products. Finally, only nine countries (20%) attempt to include uncertainty estimates of the areal statistics (e.g. error estimates associated with a forest/non-forest area map) in their NFI remote sensing-based map products. In terms of location error, only five countries (11% of respondents) indicated that either pixel or distance-based error metrics are explicitly accommodated in the map products constructed from NFI data using remotely sensed data and technologies.

3.5.3. Future possibilities

No NFI currently uses data acquired from radar or lidar sensors or unmanned aerial vehicles in an operational manner at a national scale. However, 15 countries indicated an interest in considering use of lidar data in the future. The utility of radar and lidar data has been demonstrated via multiple small-scale and prototype studies using NFI data (e.g., Solberg, Astrup, Bollandsås, Næsset, & Weydahl, 2010; Næsset et al., 2011; McRoberts, Gobakken, & Næsset, 2012; McRoberts et al., 2013; Vastaranta et al., 2013; Wulder et al., 2013). The primary impediments to operational implementation at national scales are the cost of acquiring wall-to-wall lidar data for large areas and the cost of providing each field crew with a survey grade GPS receiver at current costs of as much as $10,000 (US) per receiver. Use of low density lidar data acquired for constructing digital elevation models may mitigate costs of an initial lidar acquisition for NFI applications as demonstrated by Clement (2003) for the Netherlands, Ginzler, Boehl, Boesch, and Waser (2007) for Switzerland, and Nord-Larsen and Riis-Nielsen (2010) for Denmark; however, the cost of subsequent acquisitions must still be addressed. Until the cost issue can be resolved, possibly via a future spaceborne sensor such as the proposed Global Ecosystem Dynamics Investigation lidar (NASA, 2015), operational use of wall-to-wall lidar by NFIs at national scales will likely continue to be limited.

3.6. Case studies

Case studies for Switzerland, Finland and the USA illustrate approaches for using remotely sensed data to support NFIs that are state-of-the-art with respect to innovation, statistical rigour and cost efficiency.

3.6.1. Switzerland

Although the Swiss NFI does not wholly depend on the interpretation of aerial photograph, foregoing the use of aerial photography would result in excessive and unsustainable costs for the ground-based field survey component of the NFI. Since the introduction of aerial photography to the NFI, the image processing chain has been optimised to reduce the number of plots requiring visual interpretation. However, the time necessary to accomplish the photogrammetric tasks including pre-processing, preparation, optimisation and image interpretation is not insignificant at more than four months per year. Currently, all photogrammetric analysis is conducted by three technicians and two researchers. Data from spaceborne sensors are not currently used operationally by the Swiss NFI because of the limited temporal and spatial resolution of current satellite data products and their limited applicability and usability in Swiss topographic conditions that include relief-induced cloud cover or shadow and/or geometric correction issues over large areas as a result of steep terrain.

The Swiss NFI is a sample-based survey that has been conducted every 10 years since 1983 (NFI1). With the initiation of NFI2 in 1993, only half of the original sample plots (approximately 6500 plots) have been visited in the field because the 1-km width of the NFI1 sampling grid was extended to 1.4 km. To compensate for the reduced sampling intensity, aerial photograph were visually interpreted using a 500-m $\times$ 500-m regular grid. The black and white aerial photography used for both NFI1 (1983–1985) and NFI2 (1993–1995) was replaced by scanned aerial colour photography for NFI3 (2003–2007). Similar interpretation methods are being used for NFI4 (2009–2017) which is based on a continuous survey with plots surveyed over a period of nine years as opposed to a periodic survey. Thus, one-ninth of the sample plots systematically distributed over the land area of Switzerland are stereo-interpreted every year using digital aerial photograph. The aerial photography was acquired by The Federal Office of Topography (swisstopo) and has been available for the entire country since 2008. This aerial photography is currently being acquired on a 3-year cycle.

For NFI1 and NFI2, black and white 1:25,000 scale aerial film photograph were stereo-interpreted using analytic stereo-equipment. The aims of photo-interpretation were to reduce costs for the field survey by identifying plots clearly outside forest. In the third inventory (Ginzler et al., 2005), black and white photograph were replaced by scanned aerial true colour photograph at a scale of approximately 1:30,000 captured using a Leica RC30 aerial sensor. The stereo-interpretation of plots was conducted using 3D computer screens with polarized eyeglasses and included the follow steps:

- identification of the forest boundary (if any)
- assessment of forest/non-forest at the centre point of the plot
- assessment of height and land cover type (11 categories) at 25 sub-sampling points within a 50 $\times$ 50 m square in a regular 500 m raster (Figs. 4, 5)
- for forest plots the assessment of the forest type (six categories)
- for non-forest plots the assessment of tree attributes outside forest (height measurements of individual trees/length measurements of hedges, groups of trees)
- for forest plots on the sub-grid on the terrestrial inventory the identification and coordinates of orientation points for field crews.

For NFI4 (2009–2017), stereo-interpretation is conducted using multispectral (RGBI) digital aerial photograph from the Lecia Airborne Digital ADS80 sensor with a spatial resolution of 25 cm in areas of flat topography, and 50 cm in mountainous areas of the Alps. Aerial image interpretation includes estimation of TOF resources for biomass estimation, analysis of landscape patterns and diversity including woodland shape and connectivity, as well as estimation of tree heights and tree volume for small areas. OWL is considered part of the forest in Switzerland, whereas forest cover on other lands such as cemeteries, parks, and plantations that otherwise satisfy the definition of forest are not yet considered in the photo interpretation exercise.

To date, NFI map outputs constructed with the support of remotely sensed data have not been used to investigate the efficacy of the NFI sample design. However, future NFI plans incorporating aerial photography include the reduction of the field sample size by means of automated routines for the elimination of non-forest plots and the implementation of double sampling for post-stratification to reduce estimation errors. In the future, estimation will be pixel-based to facilitate map construction. Furthermore, there will be an increased focus on enhanced statistical tools (i.e. generalized regression estimators and plot updating) to increase the reliability and utility of map products (e.g., Massey, Mandallaz, & Lanz, 2014). Automation of the production chain to combine both the country-wide available images from the Leica ADS80 Airborne Digital Sensor and the Swiss Vegetation Height Model (VHM) (Ginzler & Hobi, 2015) will facilitate construction of wall-to-wall forest map products such as a national forest mask, a

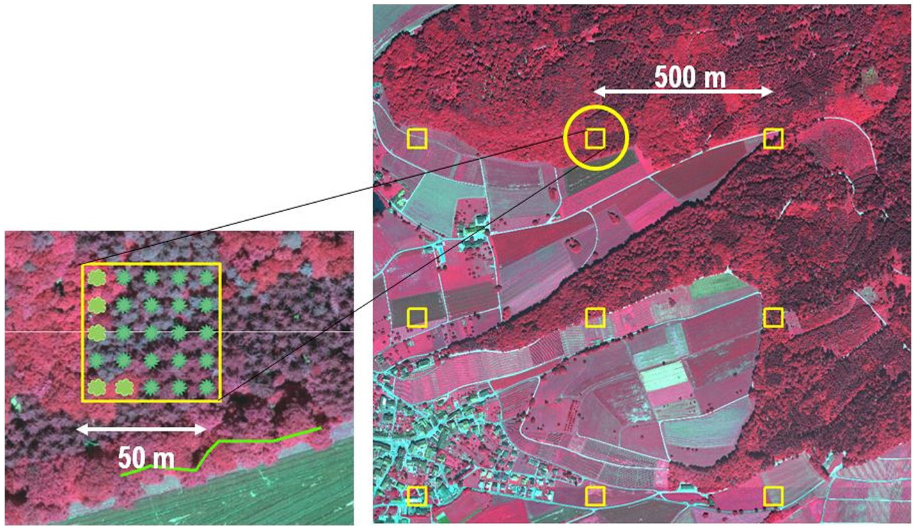

Fig. 4. Interpretation of 25 sub-sampling points of a 500 m regular raster for tree/non-tree, and deciduous/coniferous species decisions.

national tree height strata map and degree of mixture (of species) maps. The VHM is the product of a digital surface model, a thresholded Normalized Difference Vegetation Index (NDVI) (to separate vegetation from non-vegetation) and a LiDAR digital terrain model. Initial testing to automate production of these types of maps has produced promising results.

3.6.2. Finland

The first Finnish NFI, NFI1, was conducted from 1921 to 1924. Areas of site class, stand class, as well as growing stock were estimated using line sampling, and plot measurements were used to calibrate ocular estimates of stand volume and increment. Aerial photographs were first introduced and analysed in combination with field plot data in northern Finland during NFI5 (1964–1970) (Poso, 1972) with the inventory completed by region. NFI6 (1971–1976) saw the introduction of aerial photography for two-phase sampling in large areas of Lapland.

For NFI10 (2004–2008), NFI11 (2009–2013), and NFI12 (2014–present) field sample plots were surveyed across the entire country, except for Åland and North Lapland, using a new panel system, and the inventory cycle was shortened from almost 10 to five years. The current sample plot density is sufficiently large to ensure that the resulting error estimates are small for the estimates of the core variables for the

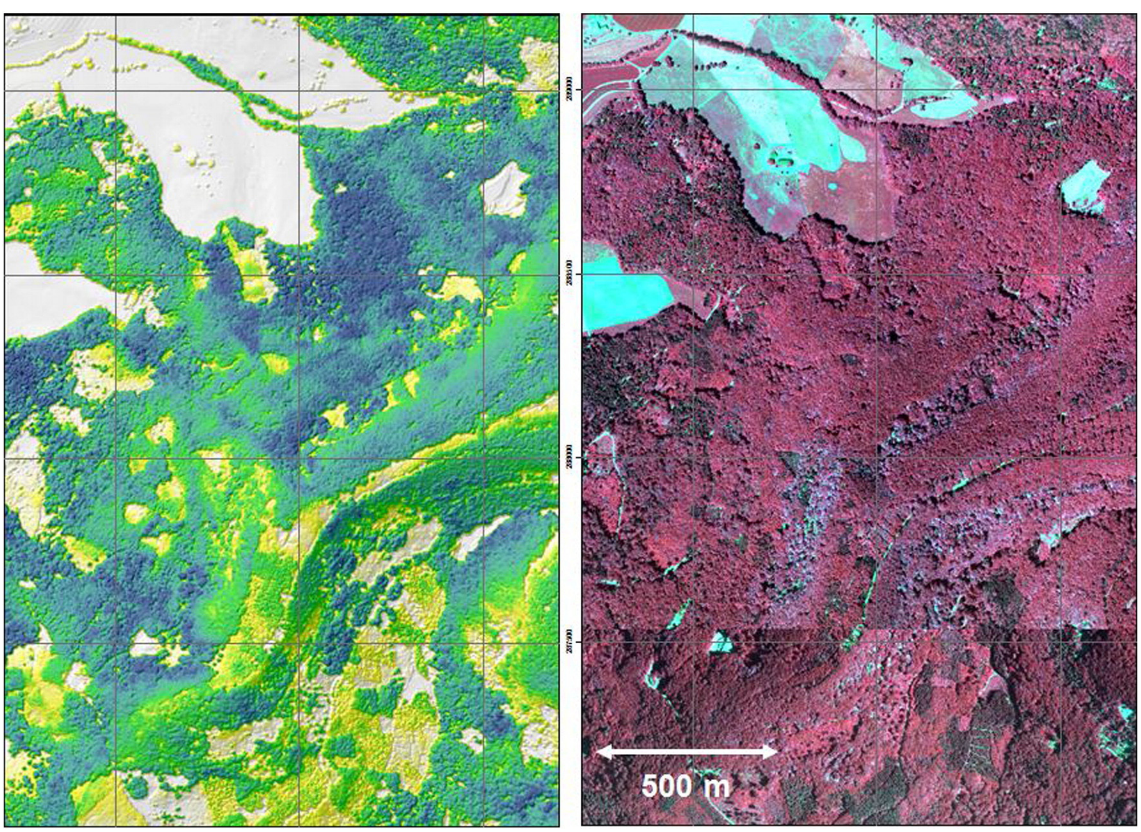

Fig. 5. Example of the Swiss vegetation height model (VHM) (left) and the corresponding colour-infrared Leica ADS80 images (right). The vegetation heights follow a colour range from yellow (low, e.g. young stands, shrubs) to blue (high, e.g. mature forest).

entire country or regions for area of forest land and growing stock. For example, the standard error of the estimate of growing stock volume for a land area of 0.8 to 5.0 million ha is approximately 2%, and at the national level is 0.6% (Tomppo et al., 2011).

The development of the Finnish MS-NFI began in 1989 during NFI8, with the first results calculated in 1990 and later for the entire country during the years 1990–1994 (Tomppo, 1991; Tomppo, Haakana, et al., 2008, Tomppo, Olsson, et al., 2008, Tomppo et al., 2011, Tomppo, Katila, Mäkisara, & Peräsaari, 2014). For the first MS-NFI, satellite image analysis methods were sought that would provide forest area and volume estimates that could be disaggregated into subclasses such as tree species, timber assortments, and stand-age classes. A further requirement for the MS-NFI method was cost-efficient estimates of forest resources for areas smaller than would be possible using field data alone, typically areas of 1000s to 100,000s of ha

In the first experiments, regression analysis and discriminant analysis were tested (Tomppo, 1988). Variables had to be predicted separately (or in small groups) in these approaches. These tests produced two main findings: 1) it was difficult to obtain a sufficient degree of detail in the information in discriminant or similar analyses, and 2) the dependence structure among the estimates generally was lost when estimates of different parameters were made independently. To avoid these drawbacks, the MS-NFI method using field plot data, satellite images and digital map data, and the k-NN technique (Fix & Hodges, 1951; Tomppo, 1991) was developed. Following the initial implementation, the k-NN estimation technique has been modified continuously and new features have been added (Katila, Heikkinen, & Tomppo, 2000; Katila & Tomppo, 2001). The core of the current Finnish method is presented in Tomppo and Halme (2004) which summarises the two key ideas of the approach: 1) the use of coarse scale variables in directing the selection of the neighbours, and 2) the weighting of the explanatory variables, i.e., spectral variables, coarse scale variables and possible map variables by means of a genetic algorithm optimisation technique. Any digital land use map or land cover data can be used to improve the accuracy of the predictions (Tomppo, 1991). The Landsat sensors (MSS/TM/ETM+/OLI) have been the principle source of satellite imagery used for k-NN estimation in Finland.

The nonparametric k-NN estimation uses a distance metric defined in the feature space of the remotely sensed and possibly other auxiliary variables. Positive weights are given to observations for the k plots that are nearest or most similar to a prediction unit with respect to the distance metric, and zero weights are given to the other plots (e.g., Tomppo, Haakana, et al., 2008). The weights are typically either equal for each of the k nearest plots or are inversely proportional to the distance or a power of the distance. The weights are then added over areal estimation units such as municipalities (Tomppo, Haakana, et al., 2008; Tomppo, Olsson, et al., 2008, Eqs. 3.12 and 3.13). The plot weights, also called plot expansion factors, can be interpreted to be proportional to the inverses of the new inclusion probabilities for the field plots. Because field plots external to the areal estimation unit (e.g., a municipality) can also have positive inclusion probabilities, k-NN estimation can be considered to be a form of synthetic estimation. The recalculated inclusion probabilities facilitate use of ratio estimators for calculating the final forest resource estimates (Tomppo, Haakana, et al., 2008; Tomppo, Olsson, et al., 2008, Eq. 3.14). In principle, estimates are possible for the entire suite of inventory parameters that are otherwise calculated using only the field plot data. In addition to areal units, estimates are often calculated for individual pixels as weighted averages of the of the observations of the variable of interest for the k nearest plots.

This procedure has been the core of the estimation method in the Finnish MS-NFI for calculating the estimates for areal units, in practice municipalities (Tomppo, Haakana, et al., 2008). Although the basic principle of k-NN estimation is straightforward, practice has shown that the predictions and estimation errors depend largely on the core estimation parameters of the k-NN algorithm and the selections made in estimation (Tomppo, Haakana, et al., 2008, Tomppo et al., 2014).

To date, seven sets of MS-NFI results have been produced for Finland at both country and regional levels. The sixth set of results, corresponding to the year 2011, were published in 2014 (Tomppo et al., 2014). The pixel level estimates in the form of digital maps are currently publicly available (Luke, 2015) with file service for publicly available data and/or viewing (National Land Survey of Finland, 2015). In the future, national level estimates are expected to be generated every second year, and then annually when country-wide satellite imagery becomes available.

Similar k-NN methods that combine field plot data and satellite imagery have been developed in several other countries including Sweden, the USA, Norway, Austria, New Zealand, Italy and China. More recently, the Finnish improved k-NN (ik-NN) method, which includes a genetic optimisation algorithm, has been successfully applied to areas in Ireland, Bosnia and Herzegovina and Spain as part of the research conducted by WG2 of COST Action FP1001.

3.6.3. United States of America

The Forest Inventory and Analysis (FIA) programme of the U.S. Forest Service conducts the NFI of the USA. Inventory estimates produced by the programme are subject to precision requirements (USDA Forest Service (USDA-FS), 1970) that are difficult to satisfy using plot data alone because of natural variability and budgetary constraints that limit sample sizes. In response, the FIA programme has a long history of augmenting ground sample data with remotely sensed data to compensate for sample size constraints. Historically, the programme used aerial photography and double sampling for stratification to increase the precision of inventory estimates (Loetsch & Haller, 1964; Hansen, 1990). In the first phase, an array of points or photo plots on the aerial photographs was visually interpreted and assigned to similarity groups or strata based on interpreted features such as forest type and age class. The proportions of photo plots assigned to strata were used as stratum weights. In the second phase, field crews visited plots located at a subset of the locations of the photo plots and obtained observations and measurements of plot attributes. Using data obtained from this double-sampling approach, inventory parameters were estimated using post-stratified estimators (Cochran, 1977).

The essence of stratified estimation is to group plots into strata, calculate within-strata estimates, and then calculate overall estimates as weighted averages of the within-strata estimates. If the within-strata means differ substantially or highly variable plots can be constrained to small strata, then the precision of the stratified estimates may be substantially greater than the precision of simple random sampling estimates. If the stratification is accomplished prior to sampling, then maximum precision can be achieved by selecting within-strata sampling intensities proportional to the within-strata variances and using stratified random sampling. However, if the sampling intensity is constant over large regions, such as is typically the case with systematic samples of permanent plots, then considerable increase in precision can still be achieved using post-stratification techniques.

In the early 1990s, the FIA programme sought alternatives to aerial photographs as a source of information for constructing strata because of labour intensity, subjectivity, and costs. In Finland, Poso et al. (1984); Poso, Paananen, and Similä (1987) had previously used stratifications based on unsupervised classifications of satellite data. Muinonen and Tokola (1990) further considered the satellite image information to constitute complete coverage of the area of interest rather than just a first-phase sample. With this approach, two tasks must be accomplished: firstly, strata weights must be calculated as the relative proportions of pixels assigned to strata, and secondly, plots must be assigned to the strata of the pixels containing their centres. However, for large areas such as states, provinces, and regions, the labour and costs associated with acquiring and processing large amounts of remotely sensed data inhibit this practice. For example, 10–20 Landsat scenes are required to cover individual states in the Midwestern region of the USA.

Hansen and Wendt (2000) first proposed using an existing satellite image-based land cover classification as a source of stratification information. McRoberts, Wendt, Nelson, and Hansen (2002b) further refined this approach using the National Land Cover Dataset (NCLD) (Vogelmann et al., 2001; Homer, Huang, Yang, Wylie, & Coan, 2004, Homer et al., 2007), a 30-m × 30-m, multi-class, Landsat-based land cover dataset. The thematic classes of the 1992 NLCD were aggregated to forest and non-forest, and four strata were then constructed: (i) forest, (ii) forest edge defined as a 2-pixel wide buffer on the forest side of the forest/non-forest boundary, (iii) non-forest edge defined as a 2-pixel wide buffer on the non-forest side of the forest/non-forest boundary, and (iv) non-forest. This approach to stratified estimation reduced variances of estimates of proportion forest area by factors as great as 3.2 for four Midwestern states and was operationally implemented by some of the regional FIA programmes.

McRoberts, Holden, Nelson, Liknes, and Gormanson (2006) later showed that stratifications based on estimates of pixel-level probabilities of forest cover reduced variances of estimates of proportion forest by factors as great as 5.9 and variances of estimates of mean growing stock volume per unit area by factors as great as 2.5. The similarity between the probability of forest cover and the percent tree canopy cover layer for the 2001 NLCD facilitated operational implementation of the latter approach to stratification. These variance reduction factors are equivalent to the factors by which sample sizes would have to be increased to achieve the same precision without the use of remotely sensed data as was achieved with the remotely sensed data. These cost savings are typically substantial.

3.7. Good practice guidelines

For countries initiating, expanding, or revising use of remotely sensed data in their NFIs, lessons learned from the responses to the questionnaire, the case studies, and the experiences of other NFI programmes can be extremely useful. To assist and facilitate such efforts, a few good practice guidelines are provided.

If NFI plot data are to be combined with satellite data with fixed resolution, the relative sizes of the plots and the pixels should be considered. A first consideration pertains to whether the pixel resolution is finer than or coarser than the plot size. If the resolution is finer than the plot size, then the issue relates to methods for aggregating data for multiple spectral bands for multiple pixels to match as closely as possible the plot area. If the image resolution is coarser than the plot size, which is typically the case for commonly used Landsat and SPOT data, then the issue is the degree to which the plot is an adequate sample of the pixel. In addition, if the plot includes multiple conditions related to factors such as forest/non-forest, forest type, or forest age and structure, then the condition proportion for the smaller plot cannot be assumed to represent the same proportion for the larger pixel. Thus, deletion of some plots from the analyses may become necessary.

Whenever data from multiple sources are combined, issues of georectification must be considered. For example, correctly matching pixels to plots whose GPS location errors are of the same order of magnitude as pixel dimensions is a difficult task, and errors may have adverse consequences, particularly for fragmented and diverse forest conditions.

A second issue related to combining data from multiple sources pertains to dates. To the degree possible, dates of remotely sensed data should be as close as possible to field plot measurement dates. Plot-level disturbances caused by harvest, storm damage, and insect and disease between the two dates can cause large errors in estimates and map products. Plots with such large changes should be either up-dated or removed from the analyses. Growth models may be applied to update data for plots that were measured in years before image acquisition (Tomppo et al., 2014).

Ranges of variation in both response and remotely sensed variables in the sample or training data should cover ranges in the same variables in the entire inventory area of interest. Predictions from non-parametric methods such as k-NN are especially susceptible to extrapolation errors resulting from inadequate sample ranges in the response and remotely sensed variables.

If consistent maps of multiple inventory variables are desired, then all map variables should be predicted for map units simultaneously and in a consistent manner using a multivariate method such as the k-NN technique (Tomppo, Haakana, et al., 2008; McRoberts, 2012).

Adequate, if not optimal, combinations of NFI field data, remotely sensed data, and analytical methods should be sought. The choice of adequate imagery, whether from airborne or spaceborne sensors, for an NFI depends on multiple theoretical, technical and practical considerations. From a technical perspective, the input data must provide the required accuracy for estimates using the selected analytical methods. This requirement may limit the acceptable spatial, spectral and radiometric resolutions. From a practical perspective, choices may be further limited by data availability and costs and analytical expertise within the NFI programme. Spatial considerations are also relevant; for example, combinations that provide sufficiently accurate results for small areas, may not do so at the national level. Revision and iterative testing of plot configurations, sample designs and sample sizes may be necessary to optimise the benefits from remotely sensed data relative to costs.

The uncertainty in forest attribute maps and map-assisted estimates should be estimated using statistically rigorous methods. For example, methods based on pixel-counting, such as estimating forest area as the sum of areas of pixels classified as forest, are inherently biased because of map prediction errors. All map-based estimates must be adjusted to compensate for prediction errors, typically by comparing map predictions and ground data for a probability sample using techniques such as the model-assisted, generalized regression estimator (Särndal, Swensson, & Wretman, 1992, Section 6.5; McRoberts, Liknes, & Domke, 2014).

4. Conclusions

Four main conclusions may be drawn from the responses to the questionnaire and the case studies. Firstly, remote sensing is now a central component for the successful operation and completion of NFIs. A wide range of traditional as well as new statistical techniques have been used in the analysis of remotely sensed data, in combination with NFI field inventory data. At the same time, a variety of auxiliary datasets have also been included and combined with NFI plot data using remote sensing methods to improve the estimation of forest parameters and variables through pre and post-stratification approaches.

Secondly, the levels of detail, scale and approaches used in NFIs vary considerably. Methods are adapted nationally, regionally or locally and are tailored to match the specific topographic, bio-climatic zones and or forest types of the areas being assessed.

Thirdly, while the application of remote sensing methods within NFI programmes has contributed to maximizing benefits relative to costs, operational integration of uncertainly estimation requires additional attention.

Fourthly, COST Action FP101 provided an effective forum for exchanging information and transferring expertise. For example, methods developed and used operationally in Finland have been modified and developed for Irish conditions (McInerney, Barrett, & Tomppo, 2014), and are under modification for transfer to Bosnia and Herzegovina and Spain.

Acknowledgements

This article is a product of Working Group 2 of COST Action FP1001 (USEWOOD). COST (European Cooperation in Scientific and Technical Research), financially supported the meetings and Short Term Scientific Missions making this work possible. We thank the respondents from 45 countries who participated in our questionnaire survey: Alberto Sandoval Uribe, Jacques Rondeux, Marc Wagner, Celina Montenegro, Conceição Moreno, Paul Lane, Claire Howell, Georgios A. Georgiou, José Uva, Marko Kovac, Novica Tmusic, Yasna Rojas Ponce, Emine Ataş, Marek Jabłoński, Nickola Stoyanov, Nicholas Py, Azra Čabaravdić, Zsolt

Magyar, Sung-Ho Kim, Graham Stinson, Annemarie Bastrup-Birk, Vivian K. Johannsen, Joberto Veloso de Freitas, Juris Zarins, Mark Lawrence, Xiangdong Lei, Björn Traustason, Daniel Nitu, Lars Waser, Veiko Adermann, Wim P. Daamen, Christoph Bauerhansl, Tomáš Bucha, Mats Nilsson, Yasumasa Hirata, Gerald Kändler, Heino Polley, Erkki Tomppo, Ronald E. McRoberts, Radim Adolt, Svein Solberg, Ioannis Meliadis, Julien Philippart, Patrizia Gasparini, Santiago Saura, Gintautas Mozgeris, Tatiana Chernenkova, Christian Ginzler.

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