Current and Emerging Operational Uses of Remote Sensing in Swedish Forestry

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Abstract.—Satellite remote sensing is being used operationally by Swedish authorities in applications involving, for example, change detection of clear felled areas, use of *k*-Nearest Neighbour estimates of forest parameters, and post-stratification (in combination with National Forest Inventory plots). For forest management planning of estates, aerial photointerpretation in combination with stand-wise field surveys is used. Automated analysis of digital aerial photos is a promising technique for tree species classification; laser scanning is being applied to assess tree height, stem volume, and tree size distribution; and low-frequency radar is being used for stem volume estimation. Obtaining timely photos of single stands from small unmanned aircraft is also an increasingly realistic option.

Introduction

Sweden has 22.9 million ha of forest land, which is managed for the production of timber and pulpwood. Half of this area is owned by a few large companies and the other half is divided into more than 200,000 private estates. Information about this forest resource is needed at three levels: (1) the authorities need overviews that encompass all forest owners; (2) the individual forest owners need more detailed information for management planning of each estate; and (3) timely information is needed about individual stands where cuttings are planned or have just been carried out. New remote sensing methods are now being introduced and tested at all of these three levels. The aim of this article is to provide an overview of this recent development in Sweden in the field of remote-sensing-aided forest resource assessment. Because much of the forestry related remote sensing research in Sweden is done at the Remote Sensing Laboratory at the Swedish University of Agricultural Sciences (SLU), a second aim is also to provide an overview of the lab's recent relevant research and to provide references to studies where more details about each topic can be found.

Satellite-Data-Aided National Forest Monitoring

Moderate resolution optical satellite imagery from Landsat or SPOT has been operationally utilized by both the Swedish Forest Agency and the Swedish National Forest Inventory (NFI) during recent years. Since 1999, the Forest Agency has annually obtained satellite images for all forest land in Sweden. The primary application is for verification of cutting permits; since 2003, cut areas have also been delineated. This verification is done by the local foresters at about 100 district offices, using tailormade Geographic Information System and image processing applications created by the Forest Agency and the Swedish National Land Survey. The change detection is based on relative calibrated imagery using forest pixel values as a spectral reference. In support of this application, the SPOT satellites have been programmed to cover all of Sweden annually during recent summers. As a side benefit, the resulting image database is useful for many other applications, such as estimates of forest parameters by combining image data with NFI sample plots.

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The Swedish NFI

The NFI design is based on an annual systematic sample of field plots across Sweden (Ranneby *et al.* 1987, Ståhl 2004). The aim is to allow reliable summary statistics for 31 counties or parts of counties, using 5-year averages of field plot data. Plots are located in square-shaped clusters that consist of either 6 or 12 temporary plots of 7-m radius or 8 permanent plots of 10-m radius. In total, about 5,300 permanent and 3,500 temporary plots are inventoried across Sweden every year. Permanent plots are reinventoried every 5 to 10 years. The plots have been positioned with the Global Positioning System since 1996, which further enables their use in combination with satellite image pixels.

The Munin Production Line

An automated production line has been developed for combining NFI plot data with Landsat satellite data. In a first step, the NFI plots are used for preprocessing of the satellite data. The local geometrical errors between the satellite data and each field plot are modeled and the most likely pixel values given this modeling are selected (Hagner and Reese [in press]). Furthermore, the correspondence between NFI plot data and the image data is also used for parameterization of a slope correction and for reducing haze differences within the individual satellite scenes (Hagner and Olsson 2004).

The first use of the Munin production line was for a nationwide classification of forest land into seven different forest classes. This work was done by SLU from 2002 to 2003 under contract with the Swedish National Land Survey and it was used as input to national and European land cover databases. In total, 50 Landsat Enhanced Thematic Mapper Plus (ETM+) scenes and 34,000 NFI plots were used. The forest classification was based on "calibrated" maximum likelihood algorithm which made use of prior probabilities. The classification of each Landsat scene was iterated until the frequency for each forest class corresponded to the frequency according to the NFI plots within the scene (Hagner and Reese [in press]).

The *k*-NN Product

The Landsat ETM+ images and the NFI plots used for the previously mentioned land cover classification were also used in production of a nationwide forest parameter database using a version of the Finnish *k*-Nearest Neighbors (*k*-NN) method (Reese *et al.* 2003, Tomppo 1993). The first "*k*-NN Sweden" database was produced with images from around 2000, and is available as a raster product with estimates of total stem volume, stem volume for different tree species, stand age, and mean tree height for each pixel. Estimates were made for all pixels defined as forestland according to the 1:100 000 topographic map. With the production line in place, generating such a database for all forest land in Sweden takes about 1 man-year including all data handling and quality checking. There is also a version of the *k*-NN product that has been generalized, using a segmentation software developed in house (Hagner 1990) to represent approximate stands.

While the pixel-level accuracy for the *k*-NN product can be quite poor, the accuracy for aggregated areas is still acceptable for many applications. Typically, the estimation accuracy for stem volume is on the order of 60 percent at pixel level, 40 percent at stand level, and 15 percent when aggregated over a 100-ha area (Fazakas *et al.* 1999, Reese *et al.* 2002, Reese *et al.* 2003). Because the relationship between optical satellite data and stem volume is poor for closed canopies, the *k*-NN product underestimates stands with high volume. In addition, standing volume in sparse areas or young forest may be overestimated.

The *k*-nn database has been used by forest authorities, environmental authorities, and the tax agency to obtain an overview of forest resources for large areas (Nilsson *et al.* 2004). It is also used in many research projects, such as species habitat modeling, as a baseline for landscape scenarios, and together with change images for analysis of storm-damaged areas. During 2006, a new version of the nationwide *k*-nn database, using SPOT images from the summer of 2005, is being produced.

Post-Stratification of NFI Estimates

Post-stratification of NFI plot estimates is presently being introduced as an operational routine. Tests show that the standard errors for estimates of total stem volume; stem volume for pine, spruce, and deciduous trees; as well as tree biomass can be reduced by 10 to 30 percent at a county level by using post-stratification based on Landsat ETM+ products compared to only using field data for the estimation (Nilsson *et al.* 2003, Nilsson *et al*. 2005). Post-stratification has proven to be a straightforward and efficient method for combining satellite data and NFI data. Most problems that might lead to biased estimates are avoided, which might not be the case using other methods.

Forest Management Planning Using Airborne Sensors

In Sweden, the forest management planning of estates is the responsibility of the land owner. In this section, remote sensing techniques that could provide stand-wise estimates useful for planning purposes are discussed. Estimation results for the most important variable, stem volume, are also summarized in table 1.

Optical satellite data with 5- to 30-m resolution pixels have been used operationally for updating of stand boundaries and could also be used for other tasks such as locating stands where shrub cleaning is needed, provided that a smooth supply of data is available. Satellite data, however, are generally not considered accurate enough for capturing basic data necessary for forest management planning. Instead, various combinations of aerial photointerpretation and field work have been used. Traditionally, the photos have been used mainly for defining homogeneous stands; however, especially for large forest holdings, photogrammetric instruments have been used as well, for measurements of tree heights and manually aided estimation of stem volumes. Aerial photography is the only terrestrial remote sensing data source in Sweden that is regularly acquired with government subsidies. During recent years, scanned digital orthophotos have become the most widely used data source for everyday work in the forest sector. In 2004, the Swedish National Land Survey acquired a Z/I Digital Mapping Camera. The experiences so far has been that the radiometric quality of these images is much better than that of scanned aerial photos.

Automated Interpretation of Aerial Photos

In our research with automated interpretation of aerial photos, we have implemented a version of the template matching method developed by Richard Pollock in Canada (Pollock 1996). This method is based on the generation of synthetic tree templates that are rendered with the appropriate illumination and view angle for each position in the image. The template trees are then compared with potential trees in the image using correlation techniques. Using template matching, studies carried out in a coniferous forest area in southern Sweden, approximately two-thirds of the trees could be found and positioned (Erikson and Olofsson 2005, Olofsson 2002). By using the digital photo pixel values associated with trees detected by template matching, we have, in early tests, separated tree species for spruce, pine, and deciduous trees for 90 percent of all detected trees (Olofsson *et al.* 2006).

Table 1.—*Stem volume estimation accuracies on stand level for different remote sensing sensors, validated at the same test site; all estimates except the photogrammetric measurements are made with regression techniques.*

Sensor or sensors used	References	RMSE (%)
SPOT HRVIR, SPOT HRG, or Landsat ETM+ satellite data	Fransson *et al.* 2004; Magnusson and Fransson 2005a.	23–31
Interpretation of aerial photos in photogrammetric instrument	Magnusson and Fransson 2005b.	18–24
CARABAS VHF SAR	Magnusson and Fransson 2004.	19
Combination of CARABAS and SPOT HRVIR	Magnusson and Fransson 2004.	16
Laser scanner	Fransson *et al.* 2004.	12

Laser Scanning

Since 1991, the Remote Sensing Lab has conducted work using laser scanning for forests (Nilsson 1996), often in cooperation with the Swedish Defense Research Agency (FOI). Two main methods for forest inventory based on laser scanning have emerged. Using low posting density laser data (on the order of one laser pulse per m^2), statistical relationships between field plot measurements and laser data features such as height percentiles can be established and then applied to all laser measured forest. This method has provided stem volume estimates with about 10 to 15 percent root mean square error (RMSE) (Næsset *et al.* 2004, Holmgren 2004). The commercial application of laser measurements for forest inventory has been pioneered in Norway. The first operational-scale test in Sweden was done in 2003 when a 5,000-ha area was laser surveyed (Holmgren and Jonsson 2004). The RMSE on stand level was 14 percent for stem volume, 5 percent for tree height, and 9 percent for mean diameter.

The other main approach is to laser scan densely enough to obtain many laser pulses per tree to detect single trees, which requires a density on the order of five pulses per m^2 or more. Today such data is primarily obtained in research mode using helicopter, but technical developments allowing very-high-density laser scanner data from fixed wing aircrafts is a realistic option for future operational surveys. One contribution to this development is the emerging Focal Plane Array technology that enables many sensor elements to record the return from each emitted laser pulse (Steinvall 2003). In one study of a coniferous dominated forest in Sweden, by using high-density laser scanner data it was possible to locate more than 70 percent of the trees that represented more than 90 percent of the stem volume; tree height and canopy diameter were also automatically measured, both with a precision of 0.6 m (Persson *et al*. 2002). Using features derived from laser data belonging to automatically detected tree canopies, we have also been able to discriminate spruce from pine with an accuracy of 95 percent (Holmgren and Persson 2004). Current work includes the combination of laser data and optical image data for improved tree species determination. The Remote Sensing Lab is also working with estimation of stem diameter distribution using dense laser scanner data (Holmgren and Wallerman 2006) and with laser-data-aided segmentation.

Airborne Low-Frequency Radar

FOI and Ericsson Microwave Systems have developed CARABAS, which is a unique low-frequency synthetic aperture radar (SAR) system (Hellsten *et al.* 1996). At present only one system is available but the development of civilian systems is being discussed. Because CARABAS operates with 3- to 15-m long radar waves in the VHF band, the radar signal penetrates the forest canopy and is reflected predominantly from the interaction between ground and tree stems. A long series of CARABAS research studies in Sweden shows the potential of VHF SAR for stem volume assessment in boreal forests. Typically the RMSE for stand level assessment of stem volume is about 20 percent. In contrast to optical imagery, no signal saturation for high stem volumes has been found for Swedish forests (e.g., Fransson *et al.* 2000). Optical satellite data is, however, better correlated with stem volume up to about 100 m^3 per ha than CARABAS data. Subsequently, the best estimation results have been obtained by combining the data sources, where satellite data is weighted more for low volumes and CARABAS data more for high volumes (table 1).

It has also been shown that wind-thrown trees often provide a stronger radar return and a different texture than standing trees, and that they often can even be detected under a canopy of remaining standing trees (Fransson *et al*. 2002, Ulander *et al*. 2005). At present a CARABAS survey is being carried out for a 15,000 km^2 storm damaged area in southern Sweden to detect remaining storm-felled trees that could contribute to increased insect populations.

Mapping of Single Forest Stands Using Unmanned Airborne Vehicles

The Swedish forests are managed with a clear felling after about 100 years. The large forest companies make special prefelling inventories to create a database that could be used to select and cut the right type of stands at any given time, according to industry needs. Today these timber inventories are entirely field based and there is a need to find remote-sensing-aided methods. In addition, after final felling, there is a need to survey the area for regeneration planning and also for documenting nature conservation actions. There is also a need to follow up the regeneration of young forest and determine the areas and timing for precommercial cleaning cuttings. The common requirement for all of these applications is a need to, at a given point in time, survey specific stands that are scattered through the landscape. In Sweden today, photographs of new clear felled areas are often taken from small aircraft, using medium format digital cameras. A future time- and cost-effective alternative could be to use small unmanned airborne vehicles (UAVs) with cameras and/or other sensors that are operated by the foresters themselves on location. Members of our group have experimented with the development of UAVs and, after a series of tests, have arrived at a model with a wing span of about 1.2 m and a weight of about 800 g. It is driven by an electric motor and can take a payload of more than 500 g. Using a standard digital camera, it is possible to take a series of 5-cm pixel photographs from an altitude of about 150 m, which can be block triangulated and corrected to map projection.

Discussion

The operational use of satellite data in Sweden has provided new opportunities for forest authorities and researchers alike. The boundaries and date of final cuttings are now well documented and the new regeneration of forests could be efficiently monitored. The combination of NFI plot data and satellite remote sensing data has provided the first nationwide map database of forest resources. Furthermore, post-stratification has provided the possibility to produce reliable statistics for smaller areas than the NFI plots alone can provide. The largest problem for the continuation of these developments is the lack of firm international long-term planning for the supply of suitable satellite data. Many of the systems that could replace the present Landsat generation only have scenes with sizes in the order of 60 by 60 km, which are more problematic to use because they encompass far fewer NFI sample plots than the Landsat scenes; furthermore, they often lack a mid infrared band, which is important for forestry. Fortunately, the United States has now made a commitment to develop a Landsat 8, but similar commitments are also needed in Europe.

In Sweden the more detailed inventories needed for forest management planning are carried out at an individual estate level and are so far seldom coordinated with neighboring properties. This is in contrast to the situation in Norway and Finland where government subsidies are used to ensure more coordinated forest mapping. Since aerial photos are the only data source acquired by a government plan, there are in reality no other data options for the small forest owners who manage half of the forest land in Sweden. The possibility of working with high-quality photos from digital surveying cameras, which could be interpreted in the new user friendly digital photogrammetric work stations, as well as the emerging possibilities to automatically interpret aerial photos, opens up new possibilities. The large forest companies that manage millions of hectares could also consider other remote sensing methods. For them, laser scanning appears to be an attractive add on to the aerial photos. For large areas, the cost of acquiring laser scanner data is on the order of 15 percent of the cost for the final forest management plan. In the boreal coniferous forest, laser scanner data will provide better stem volume estimates and equally good tree height estimates as today’s field-based methods. The field plots needed for training the laser scanner data could be used also for planning on a strategic level. Laser scanner data could also aid in automated stand boundary delineation. With future high-density laser scanner data, it will also be possible to estimate within stand stem diameter distributions and, in combination with digital air photos, it will also be possible to obtain information about tree species distributions.

The possibility to detect storm-felled trees with the CARABAS SAR is interesting, especially because the sensor is not dependent on weather or sun illumination, and is mounted on a jet plane. An operational scenario could be to survey areas with high stem volume and high risk for storm damage using CARABAS approximately every 5 years. These images could be used to enhance the stem volume estimates in databases based on optical satellite data. This combined estimate might be of sufficient quality to make it useful also for the private forest owner. The main motivation for such a regular survey, however, would be to have an early reference with radar data that could be used in change detection when new images acquired directly after a major storm should be analyzed. Because storm-felled trees will give higher radar response and ordinary cuttings and removing of trees will give a lower response, the two types of changes will not be mixed up in the radar data, which might be the case with optical data.

For timely mapping of single stands, the use of small UAVs could provide a breakthrough. Such UAVs driven by electric motors are already widely used by the military and the technology will most likely spread to civilian applications. There are no expensive or classified components needed to construct a UAV that can carry a digital camera. The main obstacle so far has been air traffic regulations, but, at least in Europe, guidelines and procedures for integrating small UAVs in civilian airspace will soon be established. Civilian professional use of small UAVs is already permitted in some countries, such as the UK and Finland, and will most likely be in others.

Even with the straight-forward, simple, and realistic approaches to remote sensing of forests discussed here, it can be concluded that we are currently in a rapid development in which new sensors and platforms, such as digital cameras, laser, radar, and UAVs, as well as a sound and realistic combination of the satellite technology and field data, provide new possibilities that will improve the supply of data about our forests. Beyond that, many new developments not discussed in this paper will provide additional possibilities over the coming 25 years. Examples include the use of time series data and data assimilation techniques; automated interpretation of high-resolution optical data using learning techniques; new laser scanner technology with very dense posting; ground based laser scanners that will be easy to handle and provide data that can be integrated with airborne measurements; feedback of data from harvester machines to similar stands according to remote sensing; and sensors onboard permanent high-altitude UAVs. One major conclusion is, however, that government policy plays a key role regarding which technically feasible data capture options will, in the end, be economically and practically feasible. This statement is valid regarding the supply of satellite data, for policies for airborne data acquisition as well as for permissions to fly UAVs.

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