Multitemporal satellite data in forest mapping and fire monitoring

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ABSTRACT

Because the Mediterranean countries are importers of forest products, one of the basic aims of forest management is to increase the production of industrial wood. Erosion control, and minimizing forest fires support this fundamental aim. Protection of the environment is an objective in its own. When information on forest resources is relatively limited, satellite remote sensing can easily give useful new information.

This paper reviews the potential of remote sensing in forest management, including ecological management in the Mediterranean area. The review is mainly based on results that have been achieved during the last 20 years of remote sensing research at VTT. Three subjects are discussed:

1. General inventory and mapping for forest management;

2. Near real time detection of forest fires; and

3. Change mapping.

In inventory for strategic planning, remote sensing can be used to reduce field work and to transform the field measurement results into maps. In forest management planning, spaceborne and airborne remote sensing should be combined. An early warning system for forest fire detection has been implemented using NOAA AVHRR data. Monitoring of changes has a great potential in forestry. To achieve a satisfactory accuracy, it is important to combine the multitemporal data sets and not to analyze the change by comparing monotemporal classifications. Research results should now be operationalized.

1. INTRODUCTION

Forest resources in the Mediterranean area are quite limited as compared to the land area and population. In the Southern European countries, the population represents 23 percent of the population in Europe. The area of productive forest represents 20 percent of the forest area, and amount of felled wood 17 percent of the felled wood in Europe. The annual amount of felled wood per capita is only 0.48 m^3/ha of which fuel wood is 0.19 m^3/ha. This is a very sharp contrast with Scandinavia where the annual amount of felled wood per capita was 6.13 m^3/ha in 1980 (Kuusela 1985).

The Mediterranean forests have suffered from non-sustainable use of timber, grazing, and forest fires for centuries. Destruction of forests have caused severe erosion problems. Due to erosion, soil has become poorer in many places.

Most of the Mediterranean forests belong to the specific Mediterranean vegetation zone which is a part of the subtropical vegetation zone. Annual amount of rain is small and it comes during Winters. Summers are hot and dry. Typical tree species of the area are conifers and leathery-leaved broadleaved trees. The number of tree species is high. Non closed forest is common and the boundary between forest and non forest is unclear. Forests are often concentrated on mountainous areas. Fire has a significant impact on forest ecosystems. Forests have only a marginal significance to the economy. Thus, information on the forest resources is not very accurate.

Because the Mediterranean countries are importers of products from the forest industry, one of the basic aims of forest management is to increase the production of industrial wood. Erosion control, and minimizing forest fires support this fundamental aim. Protection of the environment has an increased significance.

Remote sensing has a good potential in helping to meet the objectives of the forestry in the Mediterranean area. When the former information on forest resources is relatively limited, satellite remote sensing can easily give useful new information. Dry summers create good opportunities to get cloud free data using optical instruments. Frequent coverage of weather satellites, especially NOAA series satellites make possible near real time detection and monitoring of forest fires. Landsat and SPOT images, JERS-1 SAR images, and possibly also ERS-1 SAR images can be used as sources of more detailed forestry information together with the information that can be derived using digital terrain models. Sun elevation is high enough throughout the year to utilize seasonal variation in interpretation of optical images.

One of the greatest advantages, though not adequately used, is the time series nature of the remote sensing data. Remote sensing satellites give full coverage measurement data over the forests several times a day at their best. Changes in the forest ecosystem can effectively be monitored using satellite remote sensing.

Remote sensing, especially remote sensing using satellites, also has its limitations. Slopes have harmful impacts on the intensities of both optical and microwave data. Although correction of the slope effect has been studied intensively, correction of effect is difficult even if an accurate digital terrain model is available. If digital terrain models are not available on mountainous areas, the potential of SAR images is very low due to geometric and radiometric distortions. Abundance of tree species and gradual boundary between forests and non forests may require a higher spatial resolution of remote sensing data than what can be obtained by using spaceborne remote sensing. It is obvious that the best alternative is to combine spaceborne and airborne remote sensing measurements with ground measurements and map data such as digital terrain models.

This paper reviews the potential of remote sensing in forest management, including ecological management in the Mediterranean area. The review is mainly based on results that have been achieved during the last 20 years of remote sensing research at VTT. Three subjects are discussed:

1. General inventory and mapping for forest management;

2. Near real time detection of forest fires; and

3. Change mapping.

2. GENERAL INVENTORY AND MAPPING FOR FOREST MANAGEMENT

Forestry planning requirements can be roughly divided into two categories: requirements of strategic planning and requirements of operational planning. A typical inventory for strategic planning is a national forest inventory. A typical inventory for operational planning is a stand based inventory for specific forest management plan. Strategic planning needs primarily reliable statistics on forest resources, their development, and the condition of the forest. For operational planning, statistics are not enough. A stand map is needed and stand characteristic values must be reliable enough for each individual stand to enable a correct treatment decision.

In an inventory for strategic planning remote sensing can be used to reduce field work and to transform the field measurement results into maps. For instance, a multi phase or stratified sampling approach can be used (Cunia 1978, Poso *et al.* 1987). Satellite image data are first clustered into spectrally homogeneous strata. Forest characteristics values for each stratum are given according to the field plots that belong to a certain stratum (Poso *et al.* 1987). The weakness of the method is that there is no guarantee that the stratification, made using spectral data only, is optimal to estimate the forest characteristics values. In the Finnish national forest inventory, a similar approach to the stratified sampling method is applied. However, no stratification is made but the Euclidean spectral distance is computed from a pixel with field measurement data to a pixel with no field measurement data. The forest characteristics values for a pixel with no field data are given according to the field plot with shortest spectral distance (Tomppo 1991).

A method similar to the stratified sampling method, is the "regression sampling" method where the results of a supervised satellite image classification are corrected by using field measurement data and regression analysis (Burk *et al.* 1988). This method is especially suitable when estimation of some forest characteristics is more important than estimation of other characteristics. Satellite image interpretation can be optimized for the most important variables.

The methods described above may not be very appropriate in monitoring of rapid changes such as clear cuttings or mapping of burnt areas but fit better for obtaining the basic information on forest resources. When the ground truth data are from statistical sampling it is very hard to get a ground data set that is large enough for change detection. To detect changes, the best approach may be to start from the analysis of multitemporal image data. Potential changes are detected using image data only. The result is then checked, using aerial remote sensing (Häme 1991).

In strategic planning, unbiased procedure with field sample must form the basis of the inventory system. Field measurements can partly be replaced by large scale aerial surveying, aerial video imaging, for instance (Häme and Rantasuo 1988). Large scale images are a reliable tool for unbiased estimation of the extent of the forested area.

In operational planning, the number of variables of interest may be smaller than in strategic planning. A stand map must be made. A starting point for a forest management plan may be image interpretation that has been made for strategic planning. A preliminary stand map can be made using segmentation of Landsat or SPOT images. At VTT, we have successfully used a segmentation method by Narendra and Goldberg (1980) that has been further developed by Parmes and Kuittinen (1988). The method uses a region detection approach but it also has characteristics of the edge operation methods. In our tests the segment size by automatic segmentation was smaller than the stand size of the forestry map but otherwise the boundaries of the segments matched well. In other words, a single forestry stand was divided into several image segments. If this is accepted, only 12 – 25 percent of the area in stand delineation by automatic segmentation did not match with delineation by ordinary forestry mapping. An average stand size in automatic segmentation was 1.6 ha (Tomppo 1988). The average stand size in forestry map was approximately one hectare larger.

Regression analysis may have given the best results in estimation of continuous stand characteristics such as tree stem volume. However, the differences between the methods are not great. The general form of the regression model to estimate continuous stand characteristics for optical data has been in our experiments:

$$Ln(V) = a + b_1 * CH_1 + b_2 * CH_2 + ... + b_n * CH_n \quad (1)$$

where

V is predicted stand characteristic

CHk spectral feature k

a and b_k are parameters of the model

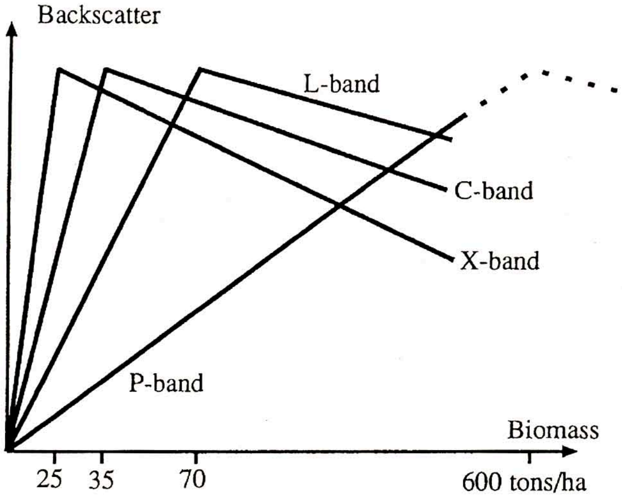

Figure 1 - Schematic representation of the radar backscatter as a function of tree biomass at P, L, C and X-band

Figure 1 gives a schematic picture of the relationship between tree stem volume and radar backscattering (Rauste *et al.* 1993). The form of the regression model, when SAR data is used is:

$$V = a + b_1 * A_1 + b_2 * A_2 + ... + b_n * A_n \quad (2)$$

where

A_k is SAR amplitude (in band k)

Other explanations: see equation (1).

In tree stem volume estimation, the coefficient of determination (R^2) of the logarithmic regression model was 0.73 when Landsat Thematic Mapper intensities of accurately measured field plots were used. The tree stem volume varied from 0 to 300 m^3/ha. The study area was in Southern Finland (Häme *et al.* 1992). Using cross-polarized P-band SAR data to estimate tree stem volume, the R^2 value was 0.5. Tree stem volume varied from 0 to 800 m^3/ha. The study area was in Black Forest, Germany (Rauste 1992). Shorter wavelength channels, L- and C-band gave poorer results than the P-band. C-band was very poor to estimate tree stem volume. Note that the presented R^2 values are not fully comparable because the model using optical data was logarithmic. The R^2 value gives a too-positive figure of the performance of Landsat data in stem volume estimation.

Intensity decrease in optical data is very limited when the tree stem volume exceeds 250 to 300 m^3/ha. It is likely that P-band SAR is better to estimate tree stem volume in high volume stands than the optical data. L- and C-bands are poorer in tree stem volume estimation than Landsat data or SPOT data. The mid-infrared channels of Landsat 5 make Landsat data more useful in forest inventories than the present SPOT data.

Maximum likelihood classification (or discriminant analysis using quadratic discriminant functions) has been as good or better than other classification methods in estimation of category variables such as site quality type (Häme 1984, Tomppo 1992, Häme *et al.* 1993). The number of observations (pixels) in the training data to compute the classification model is often so large that the statistical distribution of the data is close to multinormal distribution. If, however, category variables such as soil type, are used in classification, non parametric classifications methods, such as neural networks classification, are good alternatives (Kohonen *et al.* 1984).

3. NEAR REAL TIME DETECTION OF FOREST FIRES

Forest fires can seriously affect the sustainable timber production in large forested areas. Spreading of forest fires can also impose a threat to the safety of population. Early detection of forest fires is essential in reduction of damage. Satellite sensors operating in the infrared region of the electromagnetic spectrum can be used to detect forest fires (*e.g.* Pereira and Setzer 1993). In connection with the International Decade for Natural Disaster Reduction (IDNDR) of the United Nations, proposals have been made to establish an efficient and sophisticated satellite system to monitor natural disasters (WEDOS 1992).

Existing satellite systems can also be used to detect forest fires (*e.g.* Kaufman *et al.* 1990, Setzer and Pereira 1991). When forest fires are monitored for fire-fighting activities, image data must be acquired as often as possible. Geostationary meteorological satellites have been used to detect fires (Prins and Menzel 1992) but their resolution in thermal bands is not appropriate (Malingreau 1990). Polar-orbiting meteorological satellites (NOAA-11 and NOAA-12) offer a trade-off in terms of spatial resolution (better than geostationary meteorological satellites, worse than Earth resource satellites) and image acquisition frequency (better than Earth resource satellites, worse than geostationary meteorological satellites). A typical temperature in forest fires is around 1000 K (Pereira and Setzer 1993). The Wien's transfer law shows that the emittance peak of a black body at 1000 K is at 3.5 μm. Thus, channel 3 of the NOAA AVHRR (Advanced Very High Resolution Radiometer) instrument (wavelength range 3.55 – 3.93 μm) is very appropriate for detection of forest fires (*e.g.* Robinson 1991, Pereira and Setzer 1993).

When both channels 3 and 4 (channel 4: 10.3 – 11.3 μm) are used, the absolute fire temperature and fire area can be computed (Dozier 1981, Matson and Dozier 1981). This assumes that the background of the fire is homogeneous in terms of temperature. It also assumes that the emissivity at the channel 3 and 4 wavelengths, and reflectance in channel 3 wavelength are homogeneous over the area of the whole fire pixel. These assumptions are not necessarily true (Flannigan and Vonder Haar 1986). The requirement on the reflectance in channel 3 wavelength can be dropped if only night-time images are used (Lee and Tag 1990, Langaas 1992).

3.1 Automatic system for monitoring of forest fires

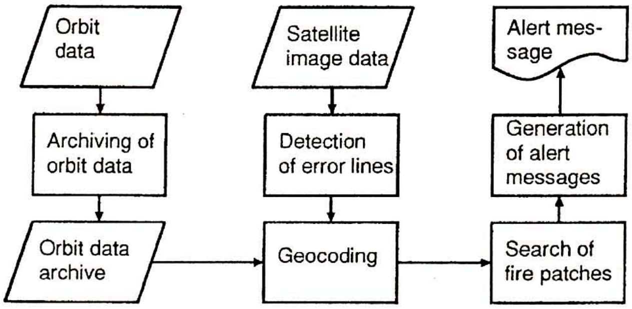

Figure 2 - Processing steps in the automatic forest-fire monitoring system

A prototype system for monitoring forest fires using image data from NOAA satellites has been developed at VTT. **Figure 2** shows the processing steps in the system. An incoming new data set is first checked for image lines that may be affected by receiving errors. Identification of lines affected by receiving errors is essential because the random digital numbers in these lines could otherwise be interpreted as fire pixels. Bad lines are marked and excluded from further analysis.

The lowest[1] digital number in the 3.5 μm channel is searched. The digital numbers were not converted into brightness temperatures to keep the system as simple as possible. If the channel 3 minimum value is below a predefined threshold, the data set is considered to include a potential fire. The pixel values of pixels in normal environmental temperature tend to form a well defined cluster towards the upper end of the digital-number scale.

1. In thermal infrared channels of meteorological satellites, the coolest pixels have been assigned the highest digital numbers and the warmest pixels the lowest digital numbers (Lillesand and Kiefer 1987, p. 597) so that cold blouds are shown in white.

The threshold value was selected so that it was well separated (over 100 units in digital number) from the cluster of the pixels in normal environmental temperature. The threshold value 32 used by Pereira and Setzer (1993) was first tried but this resulted in no fires detected. This may be due to anomalies in the analogue-to-digital conversion in the NOAA-11 AVHRR as reported by Setzer and Verstraete (1994). A higher threshold value (over 45) for channel-3 digital numbers produced a more meaningful fire detection.

After the preliminary check of potential fire-pixels, images are geocoded (rectified) using predicted orbit data. The channel 3 image is classified into fire pixels and non-fire pixels using the threshold. For all fire patches (contiguous areas of fire pixels), the following quantities are calculated:

1. Number of pixels belonging to the fire patch;
2. Minimum channel-3 value;
3. Average channel-3 value;
4. Location of the centre of gravity of the fire patch.

An electronic-mail message including these data is generated for each fire patch (**Figure 3**).

```
From: VTINSX::palokuva "Metsapalokuva" 12-AUG-1993 16:15:15.69 To: rauste
CC:
Subj: FIRE_Alert
A possible forest fire has been detected in data set:
n119308121446 (Aqcuired on 1993-08-12 at 14:46)
Channel-3 minimum: 98, 8 pixels
Co-ordinates: Northing: 4377.8, Easting: 119.0 (line: 865.9, column: 242.1)
Best regards,
Forest-fire workstation (at 93-12-08 16:16)
```

Figure 3 - An example of an alert message sent using an electronic mail system

The computation of fire temperature and fire area were not implemented in the system. In saturated pixels or in areas affected by spurious A/D conversion of NOAA-11, this could give misleading estimates of the characteristics of the fire. For fire control purposes, the most important pieces of information are the existence and location of a fire.

3.2 Forest fires detected by the automatic monitoring system

3.2.1 Fires in Finland

The automatic forest-fire monitoring system was tested during the summer season 1993. Summer 1993 was a relatively cloudy summer with no extended warm and dry period during the summer months. NOAA image data from 1 June to 20 August (with some breaks of a few days) were obtained from the Finnish Meteorological Institute. Subscenes of 1024 lines by 1024 columns (of the total 2048) were used in the test. Channels 2, 3, and 4 of the AVHRR sensor were included. The data were transmitted through a computer network to the workstation. The delay between image acquisition and image reception in the workstation was of the order of two hours. The complete analysis including production of the alert message took from two to five minutes with DecStation.

In total more than 330 images were received and analyzed by the automatic monitoring system. The system reported 66 images as containing a possible fire. These 66 images were inspected visually. In four cases, the reported fire was considered to be a real fire. Two of these fires could not be verified with fire authorities because the fires were located outside the Finnish territory. One of the fires, which was verified with fire authorities, covered an area of 30 ha. The NOAA scene where the fire was detected was acquired 1-2 hours after the start of the fire.

Most of the cases where fire was reported by the automatic monitoring system were (specular) reflections from clouds or water.

3.2.2 Fires in Greece

The automatic forest-fire monitoring system was tested using NOAA data over Greece. Data from two test periods (12-16 August, 1993 and 24-27 October, 1993) were obtained from the NERC satellite station at the University of Dundee. The data set of August contained 5 night-time images and 5 daytime images. The data set of October contained 4 night-time images and 3 daytime images. The August period was relatively cloud free whereas the October period was very cloudy.

The first of the August scenes was considered not to contain any fire. In one night-time image, a forest fire was detected. This was checked visually and it was considered as a real fire. In one daytime image, the system generated 10 fire-alerts. These were checked visually. About half of these were considered real fires. Many of the daytime images of August contained large areas where the channel 3 pixel value was similar to values in forest fires. These areas were located in mountainous parts of the images. The areas were most likely southward slopes of mountains heated by the sun in the afternoon.

No forest fires were detected in the cloudy October images.

3.3 Further development of the forest fire monitoring system

The prototype system for automatic monitoring of forest fires has problems with false alarms. Most of the false alarms were located relatively close to the border of image swath on the side of sun. Usually these false alarms were in cloudy areas or in water areas. This suggests that these false alarms are caused by reflection from clouds or from the water surface. If the sun-surface-sensor geometry is modelled in the monitoring system, the areas where this type of false alarm is possible can be excluded from the search of fire patches.

Specular reflections from water surface could also be excluded by classification of channel 2 data into classes 'water' and 'non-water'. However, a sub-pixel lake is not necessarily classified as water using channel 2 although it can cause a specular reflection. This reflection may induce very low digital counts – similar to fire – in channel 3 data. A safer alternative considers all alarms – whether from cloudy areas or water areas – in cases when specular (or nearly specular) reflection is likely to occur.

If the system is used in areas including non-forested mountains or deserts, such regions should be excluded from the search area. This can be done using a separate mask. The mask can be generated using data from the same satellites that are used in monitoring forest fires.

4. CHANGE MAPPING

Forest canopies are under a constant state of change. Long-term change is growth. Short-term change is seasonal. The main interest in change inventory in forestry is typically in measuring and estimating growth of the stem volume and in detecting and measuring rapid, exceptional changes, *i.e.* nonseasonal changes. Growth can be quite well estimated using growth models if the starting information is correct. Detection and estimation of rapid changes need ancillary measurements. Remote sensing data offer a good tool to detect rapid changes because digital images, acquired in different dates, can easily be compared with each other.

Figure 4 shows the "spectral life cycle" of a Finnish pine stand (Häme 1991). The general trend is decreasing reflectance both in the visible light and near infrared range of the spectrum (as well as in the middle infrared range). The reason for the decrease is increased biomass. In the near

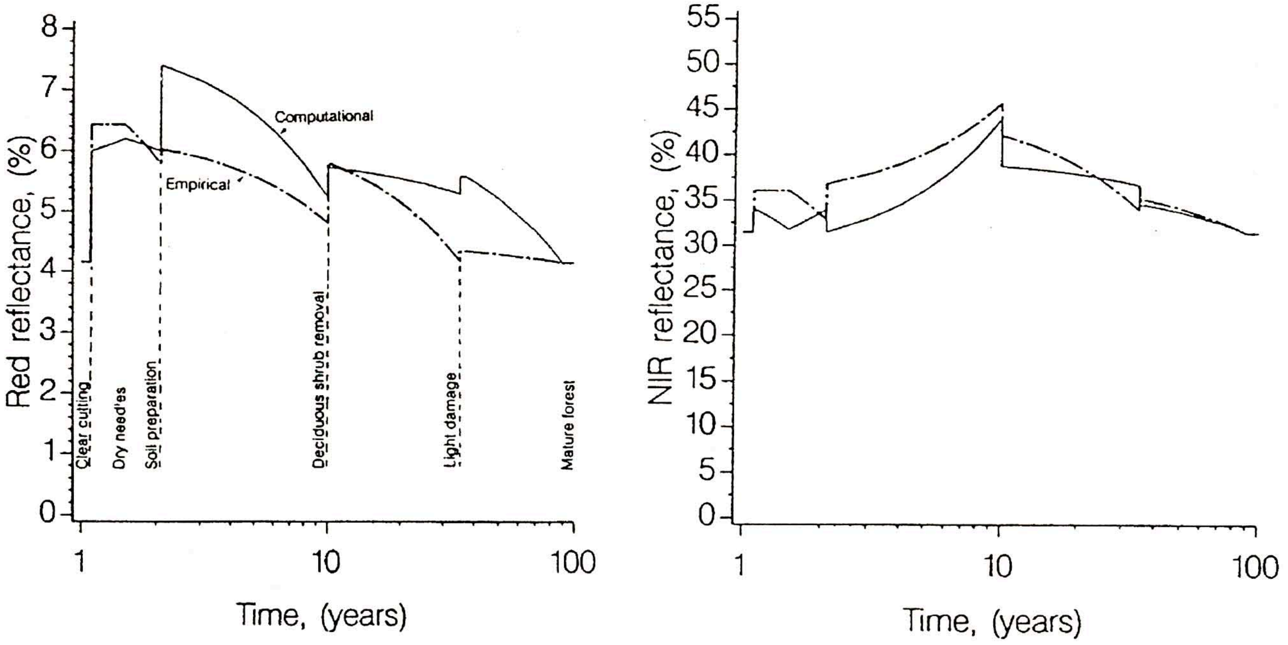

Figure 4 - Spectral life cycle of a pine stand

infrared spectral range, reflectance temporarily increases during early phases of succession. Deciduous shrubs that are abundant in regeneration areas cause the increase.

Reflectance usually increases by rapid changes because those changes destroy biomass. Spectral change due to vegetative succession is as its fastest during the early years of the succession. After the crown closure the change is small. Also the frequency of rapid changes is highest during the first decades of the life of a new tree canopy.

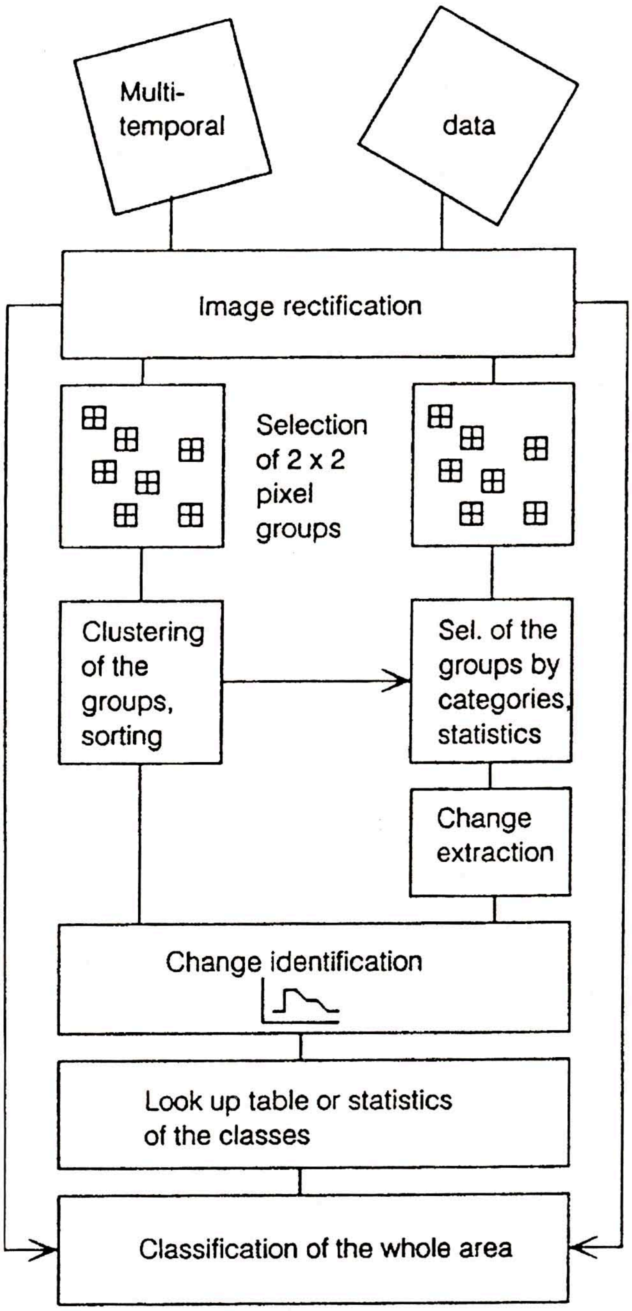

Figure 5 - Scheme for a fully automated change detection system

The reflectance model and other knowledge about changes in forest can be applied to create a fully automated system for forest change detection **(Figure 5)**. In this approach, neither careful image calibration nor comprehensive ground truth are necessarily needed. This method is most suitable for interpretation of rapid changes, such as man-made changes and damage including mapping of burnt areas. The method has the following steps (Häme 1991):

1) Geometric rectification of a bitemporal data set. An automatic feature based rectification method can be used (Holm 1992).

2) Search of homogeneous 2 by 2 pixel groups.

3) Forming 20 to 30 spectral clusters from the selected homogeneous groups using the older image only. Sorting of the clusters by biomass using their spectral statistics.

4) Selection of the 2 by 2 pixel groups from the later image by the clusters that were formed using the older image.

5) and 6) Detection and identification of the change by comparing the standard deviation of intensities in the older and later image and making a new clustering to the new image by the clusters formed using the older image.

7) Making of the a look-up table to classify the entire area of the image.

8) Classification of the whole image.

This method is under implementation. The following results in change interpretation were achieved using maximum likelihood classification of a bitemporal Landsat image set.

- Clear cuttings – performance 90 to 100 percent. In the future operative system, field or airborne checking of the performance may be necessary in training phase. Later on field checking is not foreseen. Similar results would likely be achieved in mapping of burnt forest.

- Smaller decrease in biomass than by clear cutting (fungi damage, partial storm damage, thinning cutting) – performance 60 to 90 percent depending on the intensity of the change. Aerial, possible also ground checking.

- Soil preparation – performance 70 to 80 percent. Aerial checking.

- Deciduous shrub removal – performance 60 to 80 percent. Aerial checking.

- Deciduous shrub growth – performance 70 to 80 percent. Aerial checking.

- Unchanged forest (vegetative succession only). In the future operative system, field or airborne checking of the performance may be necessary in training phase. Later on field checking is not foreseen.

The results were similar when the bitemporal original channels were used as input features or if the input features were paired differences of the bitemporal channels. Use of original channels enabled a simultaneous general classification and change classification. Use of difference channels was less demanding for the ground truth data.

5. DISCUSSION

Remote sensing and satellite image interpretation can relatively easily be connected with the general forest inventory, for instance national forest inventory. In such an inventory the main use of remotely sensed data is transformation of the field plot data into map information. Satellite data also may enable computation of forest resources statistics for smaller units than what is possible using field plot data only. However, intensity variation due to topography decreases particularly the potential of satellite remote sensing data. The topography factor could bring bias to the inventory system.

In planning for forest management plans, bias is not a problem as big as in national forest inventories but the demand for spatial accuracy is higher. Spaceborne and airborne remote sensing should be combined to achieve good enough spatial performance. No general operative systems exist to do the combination. The existing combination systems are mainly multi phase sampling systems, made for general inventory but not for forest management planning. More research should be done to create operational remote sensing aided methods for forest management planning.

Monitoring of changes has a great potential in forestry. Change detection can be utilized as well to update general forest inventory results as to update forest management plans. It also gives useful information on the dynamics of forest ecosystems. To achieve a satisfactory accuracy, it is important to combine the multitemporal data set and not to analyze the change by comparing monotemporal classifications. Change detection methods, developed at a research scale, should now be tested at operational scale.

In forest fire monitoring, it is essential that data in the 3.5 µm band (*e.g.* NOAA AVHRR channel 3) are available. This spectral band enables the detection of relatively small forest fires. Spectral bands in the visible wavelengths can also be used during night time in forest fire detection. If forest fires are monitored for fire-fighting activities, night-time monitoring has its limitations. Most forest fires start in day time. Extinguishing a forest fire is more difficult if the fire has been spreading for half a day before it gets detected. Acquisition of "night-time" images is also difficult in arctic areas around mid-summer when the darkness – if present – lasts for a couple of hours.

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