Donatas Jonikavičius

MIŠKŲ INVENTORIZACIJOS TOBULINIMAS KOSMINIŲ VAIZDŲ PAGRINDU

Daktaro disertacijos santrauka
Žemės ūkio mokslai, miškotyra (04 A)

Akademija, 2012
Disertacija rengta 2007–2012 metais Aleksandro Stulginskio universitete

Mokslinis vadovas:
Prof. dr. Gintautas Mozgeris (Aleksandro Stulginskio universitetas, žemės ūkio mokslai, miškotyra 04 A)

Disertacija ginama Aleksandro Stulginskio universiteto Miškotyros mokslo krypties taryboje:

Pirmininkas
Doc. dr. Edmundas Petrauskas (Aleksandro Stulginskio universitetas, žemės ūkio mokslai, miškotyra 04A)

Nariai:
Dr. Domantas Bručas (Kosmoso mokslo ir technologijų institutas, technologijos mokslai, matavimų inžinerija 10T)
Prof. habil. dr. Romualdas Juknys (Vytauto Didžiojo universitetas, biomedicinos mokslai, ekologija ir aplinkotyra 03B)
Doc. dr. Almantas Kliučius (Aleksandro Stulginskio universitetas, žemės ūkio mokslai, miškotyra 04A)
Dr. Vidas Stakėnas (Lietuvos agrarinių ir miškų mokslų centras, žemės ūkio mokslai, miškotyra 04A)

Oponentai:
Prof. dr. Algirdas Augustaitis (Aleksandro Stulginskio universitetas, žemės ūkio mokslai, miškotyra 04A)
Prof. habil. dr. Andrius Kuliešis (Valstybinė miškų tarnyba, žemės ūkio mokslai, miškotyra 04A)

Disertacija bus ginama viešame Miškotyros mokslo krypties tarybos posėdyje 2012 m. rugsėjo 21 d. 10 val. Aleksandro Stulginskio universiteto centrinių rūmų 261 auditorijoje, Studentų g. 11, Akademijos mst., Kauno r., 53361, Lietuva

Disertacijos santrauka išsiuntinėta 2012 m. rugpjūčio 21 d.
Disertaciją galima peržiūrėti Aleksandro Stulginskio universiteto, Lietuvos agrarinių ir miškų mokslų centro ir Lietuvos nacionalinėje Martyno Mažvydo bibliotekose.
INTRODUCTION

One of the most important parts of forest management, as a forestry planning system, is forest inventory. Forest inventory must use the latest and most advanced technologies and methodological approaches in order to obtain reliable, timely and high-quality data on forests. Lithuanian forest inventory system consists of stand-wise forest inventory (SFI), national forest inventory (NFI), inventory of mature stands (MSI) and pre-harvesting (PHI) forest inventory, which are carried out almost independently of each other, while data collected during them are hardly coordinated. Therefore, natural is the need to improve existing and to develop new solutions, which enable to increase the accuracy, reduce the price, accelerate, and expand these surveys, to combine them into a single well-functioning inventory system. One way to do this might be the use of remote sensing information. Remote sensing – receiving of information about the physical, chemical and biological characteristics of objects without direct physical contact. Currently, remote sensing techniques are widely used in forest inventory. Traditionally in Lithuania exist the opinion that due to high detailness, visualization, practical experience, traditions, etc. only aerial photos or orthophotomaps based on aerial images can be used in forest inventory, while other remote sensing data sources, such as satellite images, are unreliable, inaccurate, too expensive, etc. Due to this reason the use of medium resolution satellite images in Lithuanian forest inventory is more on a research than practical application level. However, satellite images are currently the cheapest, simply accessible remote sensing sources of information, but their successful use is always associated with different methodological principles of image processing than in the case of visual interpretation of aerial photographs or digital aerial images. Still another technological innovation of forest inventories in Lithuania in recent decades is the appearance and anchoring of geographical information systems (GIS) (Mozgeris, 1996). GIS provides essential preconditions to improve forest inventories, opens up new possibilities for remote sensing. This dissertation focuses on the vision of Lithuanian forest inventory based on integrated use of GIS and the satellite images.

Hypothesis: A combination of optimal contents, adequate quality, affordable remote sensing data, along with objective and effective processing solutions are currently major prerequisites for the improvement of forest inventory methods.

The aim of the study – improvement of on-going in Lithuania forest inventories based on satellite images and GIS databases.

Specific objective of the study – to explore the possibilities of methods applied for the collection of information from satellite images and GIS databases and its processing in order to determine various Lithuanian forest characteristics, focusing on a variety of forest inventory schemes.
The goals of the study:

1. To discuss methodological assumptions for the use of satellite images and GIS database information to estimate various characteristics of the Lithuanian forests.
2. To investigate methodological assumptions for the application of two-phase sampling scheme based on medium-resolution satellite images for the estimation of Lithuanian forest characteristics.
3. To investigate the possibilities of application of medium-resolution satellite images on the basis of two-phase sampling scheme in stand-wise, mature stands and pre-harvesting forest inventories.
4. To investigate methodological decisions and application peculiarities of fast detection of changes in the forest using medium-resolution satellite images under Lithuanian conditions.

Scientific novelty

The development of methodological background for the use of medium-resolution satellite images and two-phase sampling-based schemes in Lithuanian forest inventory.

The use of stand-wise forest inventory data as an auxiliary information together with medium-resolution satellite images in two-phase sampling schemes for the estimation of forest characteristics.

An original algorithm has been proposed based on the difference of grids of forest inventory parameters, created on the base of stand-wise forest inventory data and medium resolution satellite images, adjusted taking into account the size and shape of contours of changes, used to detect changes in the forest.

A methodological approach has been proposed to assess rapid changes in forest cover on the base of satellite images.

The practical significance

A method was proposed owing to which a close up to 2 per cent accuracy during the inventory of mature forest stands can be reached on the level of an object conducted by a forest district, forest enterprise, or stand-wise forest inventory surveyors, without essentially increasing the costs. The proposed methodical solution for rapid detection of changes in the forest can be used for forest cover change assessment, and to ensure the continuity of the State forest cadastre and stand-wise forest inventory.

Structure of the thesis

The dissertation consists of an introduction, literature review, methodology, investigation results, conclusions, references (142 references), a list of publications on the theme of the dissertation and finally annexes. The
thesis includes 22 tables and 38 figures. The general volume of the thesis is 108 pages; the volume of annexes is 14 pages.

**Material and Methods**

**Study object**

Studies were conducted in 3 objects:

1. Dubrava forest, which is in the center of Lithuania and represents most of the country's forest conditions. The total forest area of about 5400 ha. Pine stands cover 39%, spruce stands 32%, softwood deciduous 22%, hardwood deciduous 6% and other tree species take up 1% of the area.

2. Mature stands of Kupiškis forest enterprise. Kupiškis forest enterprise is located in the NE part of Lithuania. According to the data of stand-wise forest inventory, on 01.01.2009 there were 2023 forest compartments, described as mature stands with the total area of 3137.2 ha. 43% of the total area of mature stands comprise birch stands. Pine stands cover 9%, spruce stands 22%, hardwood deciduous 1%, other softwood deciduous 25%.

3. Forests in the impact zone of the wind storm of 2010 08 08 are located in 7 forest enterprises: Kaišiadorys, Prienai, Trakai, Alytus, Valkininkai, Dubrava and Varėna. The total forest area used in the study makes up 117 thous. ha. The greatest portion, i.e. about 65 thous. ha comprise pine stands, spruce stands about 20 thous. ha, hardwood deciduous about 3000 ha, softwood deciduous 28 thous. ha, other tree species about 200 ha.

**Field measurement data**

In Dubrava forest the data of two types of field located and measured sample plots were used:

1. In 1999, the specialists of State Forest Management and Inventory Institute selected seven blocks with a different forestry regime, stand species composition, site conditions, and age (Nuotolinių. ... , 1999). In each block systematically were located sample plots keeping to 35x35 m grid, with 8 sample plots falling per 1 ha – in this way it was sought to represent each forest compartment. Totally 1986 sample plots were located. In all the sample plots detailed measurements were carried out and the obtained data were processed in accordance with the rules of the National Forest Inventory.

2. In 2008 – 2009, in Dubrava forest 457 circular sample plots were field located and measured. In all the sample plots the following parameters were determined for each tree: the azimuth and distance from the plot center, species, height, development (Kraft) class, diameter in mm, the place of the largest crown diameter at relative height, defoliation of coniferous trees (crown density). Then the volume of all trees in the sample plot was calculated using standard NFI algorithms.

In 2008, in mature stands of Kupiškis forest enterprise 579 circular sample plots were field located and measured. The measurements were carried out by
the specialists of the State Forest Management and Inventory Institute. The plots were located taking into consideration prevailing tree species and age of the mature stands. The measurements and data processing was done in accordance with the prepared by the State Forest Service ‘Inventory of mature stands by sampling method’. In each sample plot all trees were measured, determining their total and the volumes of merchantable wood, firewood, waste and branches, which were estimated applying standard NFI algorithms. Geographical position of a sample plot was ascertained by the GPS Trimble Pathfinder ProXR device with 2 m accuracy.

**Information on clear cut areas used in the studies**

In the study data on delineation of final felling areas provided by Dubrava EFTE specialists were used. The felling areas were measured in 2008 and 2009, conducting conventional in the forest enterprises procedures of stand preparation for final felling (PMI). Totally 19 cutting areas were selected, where the data on the distribution of the number of trees by diameter are known based on callipering of all trees. The average area of a cutting site was 1.63 ha, the total growing stock volume - 394.5 m³/ha. The mean square error determining growing stock volume of a cutting site was lower than 10 %. The boundaries of cutting sites were measured using GPS device with 2 m accuracy.

**Information of stand-wise forest inventory**

In the work GIS data of the State Forest Cadastre on the level of forest compartments were used:

• The boundaries of Dubrava forest compartments were determined in 1988 during stand-wise forest inventory and transferred to the digital GIS database (Mozgeris, 2000). Data of the attributes of forest compartments were used as they were ascertained in 1988 during inventory and updated (using growth simulation models) to represent the condition on 1 January 2002.

• Data on stand-wise forest inventory of 2002 in Dubrava forest. The attributes of forest compartments (using growth simulation models) and boundaries (using orthophoto maps of the year 2008) were updated as well to conform to the condition on 01.01.2009.

• Stand-wise forest inventory data of 2003 in Kupiškis forest enterprise, the characteristics of forest compartments were updated using growth models to conform to the condition on 01.01.2009.

• The boundaries of forest compartments occurring within the wind storm zone on 8 August 2010 along with the information on attributes were updated (using growth models) to conform to the condition on 01 01 2010.

**Satellite images used in the studies**

Used in the study medium resolution satellite images are listed in Table 1.
Table 1. Medium resolution satellite images used in the study

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Scene ID</th>
<th>Acquisition date</th>
<th>Resolution, m</th>
<th>Research object</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT 4 HRV2, Xi</td>
<td>078/238</td>
<td>1999.08.01</td>
<td>20x20</td>
<td>Dubrava forest</td>
</tr>
<tr>
<td>Landsat 5 TM</td>
<td>187/021</td>
<td>2007 05 28</td>
<td>30x30</td>
<td>mature forests in Kupiškis SFE</td>
</tr>
<tr>
<td>Landsat 5 TM</td>
<td>187/022</td>
<td>2007 09 17</td>
<td>30x30</td>
<td>Dubrava forest</td>
</tr>
<tr>
<td>Landsat 5 TM</td>
<td>187/022</td>
<td>2010 06 05</td>
<td>30x30</td>
<td>Forest damaged by wind storm in 2010 08 08</td>
</tr>
<tr>
<td>Landsat 5 TM</td>
<td>187/022</td>
<td>2010 09 17</td>
<td>30x30</td>
<td>Forest damaged by wind storm in 2010 08 08</td>
</tr>
</tbody>
</table>

Satellite images were radiometrically and geometrically corrected. Geometric correction was done using ground control points, ascertained in topographic maps as well as by geodetic and photogrammetric measurements. Satellite images were transformed into LKS94 system of coordinates. In further analysis only the fragments of images covering research objects were used.

Other GIS data used in the study

In the study other data organized based on GIS principles were used as well:

1. GIS data on silvicultural measures applied in Dubrava forest in the period 1988 - 1998.
2. GIS database on forest areas damaged by the wind storm of 2010 08 08, where the boundaries of damaged compartments or their parts are provided along with site damage percentage (0, 5, ..., 95, 100 %), type (1 – storm damaged stands not cleared; 2 - storm damaged stands cleared, 3 – essential crown density decreased but reason unknown; 4 - essential crown density decreased but probably not for cuttings) and class (0 – damage percentage 0; 1 - damage percentage 5-25; 2 - damage percentage 30-50; 3 - damage percentage 55-75; 4 - damage percentage 80-100) (Škvalo pažeistų..., 2010).

Methods of data analysis

The studies focus on the estimation of forest characteristics using two-phase sampling method (also known as 'the model of point-wise forest characteristics'). Its essence – creation of a systematic high intensity 1st phase network of sample units (plots) in the inventoried forest territory. In each of the account units are ascertained indicator values (1st phase) of auxiliary information used in inventory. Auxiliary information – any information correlating with the inventoried phenomenon, e.g. satellite images, other information of remote sensing, data of stand-wise forest inventory, general data
of GIS databases, and so on. Field-measured or determined in other ways actual values of forest parameters in sample units (2nd phase), in which the values of the same auxiliary information parameters are known as well. Forest parameters in all 1st phase sample units are determined by various combinations of the information of the 1st phase (auxiliary) and 2nd phase (field–measured). In the work the methods of k-nearest neighbour and MSN – most similar neighbour were applied to obtain forest parameters in the sample units of the 1st phase.

First of all, an optimal kNN method application tactics was sought for depending on concrete conditions, trying to define whether specific auxiliary information in Lithuania – stand-wise forest inventory data available for the whole territory of the country – allows to improve the accuracy of the obtained results.

The following application aspects of kNN method were discussed:

1. Influence of the number of sample units of the 2nd phase on the accuracy of the obtained results. As an auxiliary information, original SPOT Xi, i.e. non-transformed satellite images were used. k number in this case was equal 5.

2. Three determination methods of k nearest neighbour weights \( w_{(i),p} \) were assessed:
   
   1) \( w_{(i),p} = \frac{1}{k}, \) t.y. \( ^\wedge m_p \) is arithmetic average of parameter \( M \) values in the closest cells \( k \) up to \( p \). This method is further indicated by SV1; (1)
   
   2) \( w_{(i),p} = \frac{1}{d_{(i),p}} \sum_{i=1}^{k} \frac{1}{d_{(i),p}} \), indicated by SV2; (2)
   
   3) \( w_{(i),p} = \frac{1}{d_{(i),p}} \sum_{i=1}^{k} \frac{1}{d_{(i),p}^2} \), indicated by SV3; (3)

   Here \( d_{(i),p} \) is Euclidean distance of the 1st phase sampling unit \( p \) in n-space of auxiliary information to the sampling unit \( i \) of the 2nd phase.

3. The influence of the number of nearest neighbours (number \( k \)) on the accuracy of the obtained results was evaluated. Determining inventory parameters in the 1st phase sampling unit by kNN method, the number of closest to it 2nd phase sampling units, or the value of parameter \( k \), was used from 1 to 20.

4. The significance of stand-wise forest inventory information, as an auxiliary information source for the accuracy of prediction, was assessed. Auxiliary information was used (i) in the original form, e.g., SPOT Xi bands digital numbers up to 255, or (ii) transformed into principal components. In the work, 2 methods of calculation of principal components were used: (i) correlation matrix was applied, i.e. original values were standardized; further it is identified as PK1 and (ii) covariance matrix was used, i.e. original values were not standardized; it is identified as PK2.
The accuracy of forecast is expressed by a bias and mean square errors (VKP) according to the determined by the study method in the 1\textsuperscript{st} phase sampling units and field-measured principal inventory parameters. The data of sampling plots were usually divided into two parts, one of which was used to make predictions, another – for validation. Errors were expressed in relative values from the error obtained applying one of the methods, or from the mean value of inventory parameter, based on the data of all sample plots of the 1\textsuperscript{st} phase used for the validation.

**Improvement of the inventory of mature stands using satellite images**

Growing stock volume of mature stands in Kupiškis forest enterprise was estimated with the help of classical two-phase sampling scheme. Sample units of the 1\textsuperscript{st} phase comprised systematically generated network of points located every 25x25 m. Totally in mature stands were located 51367 sample points of the 1\textsuperscript{st} phase. Sample units of the 2\textsuperscript{nd} phase were selected seeking to represent all the conditions of mature stands. All the 1\textsuperscript{st} and 2\textsuperscript{nd} phase sampling units were provided with cell numerical values of Landsat TM satellite image, obtained on 28 05 2007. The characteristics of mature stands were determined by kNN method. In all cases SV2 and k=10 were used. Tactical approach of kNN method was applied to estimate the weight of each 2\textsuperscript{nd} phase sampling unit for a concrete estimation object.

Growing stock volume was determined for the following objects: forest enterprise, forest district, territory inventoried by stand-wise method by engineers (there were 5 of them, named A, B, C, D, and E), economic section. At the same time total variance, mean variance and mean error in absolute and relative values of the inventory parameter were calculated.

Mean error in relative values was compared with the relative error, which would be obtained if the volume of a corresponding object was calculated using only field-measurement data.

**The use of medium resolution satellite images to estimate growing stock volume of a forest compartment**

In Dubrava forest were generated grids of 30x30 m, 16x16 m and 8x8 m systematically locating sampling units of the 1\textsuperscript{st} phase - 'virtual sample points' (also known as the X variables), which covered all prepared for final felling compartments used in the study. For each such point satellite image values were extracted, which are called X variables. Here the methods of the nearest neighbour and bilinear interpolation were applied for the extraction of satellite image values.

Stand characteristics ascertained in 2008 in measured in Dubrava forest sample plots, are called Y variables. Y variables are divided into: (i) ascertained in all sample plots (ALL), and (ii) ascertained in sample plots only within mature stands (M).
Predicted were the total growing stock of stand and volume per 1 ha. The used approaches of non-parametric kNN and MSN methods further are indicated according to the number of closest/most similar neighbours: kNN\(_{10}\) (k=10), MSN\(_1\) (k=1) or MSN\(_{10}\) (k=10). The growing stock volume of a compartment is calculated as an arithmetic mean of the predicted volume of X variables located inside the polygon of a corresponding compartment.

Seeking to evaluate the peculiarities of spatial location of X variables’ prediction errors on the level of an individual sample unit, we have generated 6, 12, 18 and 24 m buffer zones to the interior of the compartment. In this way the area of the studied polygon was reduced and it was observed what influence it had on spatial autocorrelation of predicted errors of X variables.

The volume of compartments estimated by the methods of pre-harvesting forest inventory (M\(_{VAL}\)) was used to evaluate the accuracy of the predicted volume (M\(_{MOD}\)) based on the following parameters:

1. Root mean square deviation (RMSD), calculated by the formula:

\[
RMSD = \sqrt{\frac{1}{19} \sum_{n=1}^{19} (M_{MOD,n} - M_{VAL,n})^2}
\]  

2. The portion of compartments, the forecasted and measured volume of which differed by more than 10% (SH\(_{10}\)) and more than 20% (SH\(_{20}\)), in per cent.

3. Difference between the measured and predicted total (\(D_T\)) and mean (\(D_{1ha}\)) growing stock volume in all compartments, in per cent.

The use of medium resolution satellite images to detect changes in the forest

The created grids provide surfaces of different forest characteristics, i.e. numerical values of satellite image cells were exchanged by the values of inventory parameters. For the purpose, kNN method, measurement data of sample plots and the following auxiliary information were used: SPOT Xi satellite images, data of stand-wise inventory of 1998 and 2003. The grids were created to provide the following stand characteristics: mean diameter of the storey (on an average equals 26.1 cm according to the data of sample plots), height (22.1 m), basal area (21.6 m), age (62 years), volume per 1 ha (252.9 m\(^3\)), percent of coniferous tree species (by volume) in stand species composition (69%), percent of hardwood deciduous tree species within stand species composition (7%) and the percent of softwood deciduous species within stand species composition (24%). In all cases the following settings of kNN method were used – k=10, SV1 and SPOT Xi digital numbers of satellite image bands in the original form, i.e from 0 to 255.

To determine the changes, the following algorithm was suggested:

1. Volume per 1 ha (or other forest parameter, for example, age) from the 1988 y. inventory is converted to raster. Cell size did range 20x20 m, 10x10 m and 5x5 m.
2. Grid of kNN estimated forest characteristic (say, volume per 1 ha) is subtracted from the grid, generated from stand-wise forest inventory vectors using volume per 1 ha as the value field.

3. Reclassify – IF DIFFERENCE < -127, THEN 1, ELSE 0. Value of 127 corresponds to the point-wise root mean square error that was achieved in kNN estimation.

4. The result achieved is multiplied by binary mask raster where 1 corresponds the areas of interest - clear cut areas and forest areas, and 0 – all other areas and forest nearer than 10 m from the open areas, roads and waters.

5. Reclassify - IF PRODUCT = 1, THEN 1, ELSE NoData

6. The area of continuous cells with value 1 is estimated using functions REGION GROUP and ZONAL AREA.

7. Reclassify – IF AREA < 800, THEN 0, ELSE 1. It means that all areas smaller than 2 cells are filtered out (clear cut areas can not be less, so we assume that all smaller areas are natural gaps in forest canopy or assessment noise).

8. Continuous cells with value 1 are grouped and considered as a starting point for geographic manipulations to identify the final CHANGE class.

This algorithm was implemented in the ArcGIS ModelBuilder environment and uses the basic spatial analysis functions of ArcGIS software.

Estimation accuracy of changes was evaluated considering the boundaries of forest compartments, identified during SFI of 2002, as the standard. Selected were all stands of 15 or less years in age, i.e. all areas where clear cuttings could be performed over the analysed period (since 1988). Estimation accuracy was verified overlaying binary grids: [Cuttings according to kNN data (1) AND no cuttings according to kNN data (2)] X [Cutting according to SFI data of 2003 (10) AND no cuttings according to SFI data of 2003 (20)].

Seeking to increase identification accuracy of changes in the forest, two filtering techniques of achieved CHANGE grids were suggested (Figure 1). In the first case, in the obtained CHANGE grid groups of cells consisting of from 4 to 13 cells were filtered out.

![Figure 1. Forest changes produced using different geographic manipulation techniques, CHANGE class is presented here in gray: a) no adjustment, b) MINAREA, c) EROSREC](image-url)
This filtration method (further called MINAREA) eliminates small groups of cells where high change of wood volume has been recorded. In the second case, around all cells of the grid, identified as a 'change', buffer zone is generated to the inner side of the group of cells. Generated were 0.5, 1, 1.5 and 2 cell size buffers. Then around the remaining groups of cells were generated buffers of the same width in the opposite direction (further this method is called EROSREC). In this way were discarded small groups of cells where high volume change was recorded, and at the same time were eliminated narrow and long fragments.

Estimation accuracy of the changes was assessed by considering GIS data of silvicultural measures applied in 1988 - 1998 in Dubrava forest as the standard. Confusion matrices were created and the accuracy of the 'producer' and 'user' as well as \( \kappa \) statistics were estimated (Lillesand and Kiefer, 1994; Lillesand et al., 2008).

**Application of medium resolution satellite images for a rapid assessment of the extent of wind storm consequences**

First of all, satellite image obtained on 2010 09 25 was calibrated by the relative method (Olsson, 1994) using multiple regression:

\[
\hat{Y}_b = a_0 + a_1 X_{TM1} + a_2 X_{TM2} + a_3 X_{TM3} + a_4 X_{TM4} + a_5 X_{TM5} + a_6 X_{TM7};
\]  

(5)

Where:  
\( \hat{Y}_b \) – calibrated pixel value for each band (b) of the later image;  
\( a_0, a_1, \ldots, a_6 \) – regression coefficients;  
\( X_{TM1}, \ldots, X_{TM7} \) – original pixel values of the later image.

Calibrated were only those cells of the satellite image which occurred in the forest.

Later, from the grid representing a certain spectral band of a satellite image on 2010 06 05 was subtracted calibrated grid of the same spectral band of a satellite image obtained on 2010 09 25. The obtained differences in all spectral bands were summarized (i.e. one cell value \( X_{TM} \) was determined) by the following formulae:

\[
X_{TM} = \sqrt{X_{TM1}^2 + X_{TM2}^2 + X_{TM3}^2 + X_{TM4}^2 + X_{TM5}^2 + X_{TM7}^2};
\]  

(6)

Where:  
\( X_{TM1}, \ldots, X_{TM7} \) – image difference values of corresponding TM bands

Simple thresholding of the aggregated difference image was applied to create binary “change/no change” masks, stored as raster grids with the same properties as the satellite images. Value of \( Y_{TM} \) was iteratively changed from 1 to 20, using step equal to 1, and 20 versions of “change/no change” grids were generated. Our initial guess was that, in addition to the \( Y_{TM} \) value, the interpretation of change in the validation data set could have some influence on
the interpretation of the results. Thus, based on the vector data of mapped wind damage extents, a series of raster grids was constructed to represent actual change due to wind damage. Polygons (forest compartments or parts of forest compartments) with the percentage of stand volume damaged larger than, respectively, 50, 60, 70, 80, 90 and 100, were converted to raster grids using the same grid properties as for the aggregated image difference image. Then the error matrixes (Lillesand et al., 2008) were created to assess the classification accuracy for all combinations of $Y_{TM}$ and percentage of stand volume damaged values.

Having determined the value of $Y_{TM}$ which resulted in highest overall accuracy of change classification (actually, 13), percentage of area changed for each forest compartment was calculated based on corresponding “change/no change” grid.

In addition to the spatial location of wind damaged forest areas, the volume of damaged forest stands is considered to be equally important in Lithuanian forestry. Information on total stand volume in the forest compartment is usually available from the stand register of State forest cadastre. Two solutions were used to get the wind damaged stand volume for the compartment:

1. Stand volume available from the stand register was multiplied by the percentage of area changed, determined individually for each compartment using the “change/no change” grid (Solution 1).

2. Special approach integrating the solutions originating from satellite imagery based change detection and the nearest neighbour techniques was developed (Solution 2). This approach is based on the k-nearest neighbour prediction and uses auxiliary information from the “change/no change” grid and stand register of the State forest cadastre. The following settings of $kNN$ method were used – $k=10$, $t=1$.

Based on GIS database of wind storm damaged forest areas, the total growing stock volume loss in the object was calculated, which was compared with the results obtained on the basis of satellite images and SFI data.

**Software used in the studies**

All calculations based on non-parametric methods were done using Most Similar Neighbour (Moeur and Stage, 1995; Crookston et al., 2002), modules of SMI system designed at Helsinki University, as well as a free REFE program. Standard GIS, packages of software for the processing of remote sensing information and statistical analysis (ArcGIS, PCI Geomatica, MS Excel et al.) were applied for the data preparation and analysis of results.
Results

Peculiarities of the application of two-stage sampling method based on medium resolution satellite images for the estimation of Lithuanian forest characteristics

Increasing the number of sample units of the 2nd phase from 99 to 1788 it was observed that both bias and mean square errors decrease (Fig. 2). In further studies it was decided to use 1/3 (662) of all sample plots as sampling units of the 2nd phase, as using more sample plots, MSE is obtained insignificantly, only by 1% lower. The remaining 2/3 of sample plots were further used as sampling units of the 1st phase.

SV1 weight ascertainment method is the simplest solution, thus the obtained errors applying SV1 weight were equalled to 100%. However, in the case of application of SV1 weight determination method, most parameters were estimated with by 1 - 14% higher mean square error. In the case of SV2 the obtained errors are insignificantly lower than SV3, thus further, assessing other aspects of kNN method application, weights were ascertained using namely the SV2 method, i.e. applying inverse distance weighted scheme. Assessing the influence of additional information of stand-wise forest inventory on the accuracy of obtained results, SV1 weight calculation method was applied as well.

Applying the kNN method, a very important factor is the number of nearest 2nd phase sample units, i.e. the value of k variable. Changing k value from 1 to 20, it is observed (Fig. 3), that bias of forest parameters decreases until k reaches 5–6, then starts its stable rise in the cases of all forest variables estimates. Mean square error (Fig. 4), on the contrary, with increasing k value, decreases all the time, while when k reaches 10, mean square error decreases by 19 – 25% and further increasing the value of k, remains practically almost stable. Seeking to obtain the lowest bias and mean square error, in further studies we used k=10.
Fig. 2. The influence of the number of second phase plots on the assessment accuracy of forest variables; bias on the left side, mean square error – on the right; a) and b) diameter, c) and d) basal area, e) and f) height, g) and h) age, i) and j) volume per 1 ha.
Fig. 3. The dependence of bias of forest variables estimates on the number of $k$; a) diameter, b) basal area, c) height, d) age, e) volume per 1ha

Fig. 4. The dependence of mean square error of forest variables estimates on the number of $k$

In this study the information of SPOT images and forest parameters was combined using transformations of the principal components. Accuracy, obtained using only satellite images as auxiliary information, was equalled to 100 %. If, apart from SPOT images, forest parameter ascertained during stand-wise forest inventory is used as an auxiliary information, then the value of mean square error of estimation by kNN method in most cases decreases by 4-20 %, depending on what forest parameter was used as an auxiliary information (Fig. 5).
Another possible application of stand-wise forest management information – to use the data of forest compartments to stratify the sample plots. If sample plots are used not on the entire area, but only those which according to the data of stand-wise forest inventory occur within a forest stand, prediction accuracy improves in most cases – both bias and mean square errors decrease. Fig. 6 illustrates only one, the most characteristic case of experiments.

Sample units were divided into classes according to the growing stock volume per 1 ha of the forest compartment where this sample unit is located (a similar distribution is possible according to other forest variables). The following classes of growing stock per 1 ha were used: from 1 to 20 m³/ha; 21-100 m³/ha; 101-200 m³/ha; 201-300 m³/ha and over 300 m³/ha. Inside the class prediction by kNN method was done using only the SPOT images. The obtained results are illustrated in Fig. 7. In all cases relatively the highest values of mean square errors...
were obtained in young stands, i.e. in stands, the growing stock volume of which per 1 ha comprises up to 20 m$^3$/ha. Practically independently of the forest parameter or kNN method application peculiarities, mean square error in this part of the stand comprises 50-100% from the mean value of a concrete forest parameter. However, in other volume classes mean square error by its relative value quite often is lower than the obtained in earlier experiments. For instance, mean square error of the estimated growing stock volume of mature stands comprises 38-39% form the mean value of the parameter.

Fig. 7. The mean square error of k-NN estimation of main forest variables, expressed in percents of average stand characteristic and using pre-stratification of sample plots by volume per 1 ha classes according to stand-wise inventory data. Black line identifies the lowest mean square errors achieved in previous investigations; a) diameter, b) height, c) basal area, d) age, e) volume per 1 ha and f) percent of coniferous tree species

The mean square error on a level of sample unit of the 1$^{st}$ phase estimated by discussed here methods comprise: 27% of mean stand diameter, 20% of
mean height, 40% of basal area, 35% of mean age, 43% of growing stock volume per ha, 33% of the index of coniferous percentage.

The use of medium resolution satellite images for the inventory of mature stands

Applying methods described in the thesis, it was found (with 2% accuracy) that mean growing stock volume of mature stands in Kupiškis forest enterprise comprises 297.7 m³/ha, i.e. it is by 10.3% (27.8 m³/ha) higher than the one ascertained by stand-wise forest inventory. By kNN method, using satellite images as an auxiliary information, mean growing stock volume in separate forest districts was determined: in Alizava forest district 271.9 m³/ha (with 2% accuracy), Subačių forest district 321.4 m³/ha (with 1.9% accuracy), while in Skapiškis, Kupiškis and Šimonių forest districts, respectively 288.2 m³/ha, 292.3 m³/ha and 314.5 m³/ha. Growing stock volumes obtained during stand-wise forest inventory in the forest districts differed. They were by 5.5-15.8% lower than the results obtained in this study.

Mean growing stock volume of stands ascertained by kNN method was characterized by a 2.0% relative standard error (RSE) both for the areas inventoried by certain forest inventory engineer of the Lithuanian Forest Inventory and Management Institute (LFIMI) (Table 2), and in the area by tree species (Table 3).

Table 2. Growing stock volumes of mature stands by stand-wise forest inventory objects

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter</th>
<th>Forest inventory engineer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>kNN method</td>
<td>Volume per ha</td>
<td>296.1</td>
</tr>
<tr>
<td></td>
<td>RSE, %</td>
<td>2.0</td>
</tr>
<tr>
<td>Stand-wise forest inventory</td>
<td>Volume per ha</td>
<td>273.3</td>
</tr>
<tr>
<td></td>
<td>Difference, %</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Table 3. Growing stock volumes of mature stands by dominant species on sites identified during stand-wise forest inventory

<table>
<thead>
<tr>
<th>Dominant tree species</th>
<th>Whole stand</th>
<th>kNN method</th>
<th>Stand-wise method</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume, m³/ha</td>
<td>RSE, %</td>
<td>Volume, m³/ha</td>
<td>%</td>
</tr>
<tr>
<td>Pine stands</td>
<td>313.9</td>
<td>1.9</td>
<td>289.9</td>
<td>8.3</td>
</tr>
<tr>
<td>Spruce stands</td>
<td>330.1</td>
<td>1.9</td>
<td>314.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Oak stands</td>
<td>270.8</td>
<td>2.0</td>
<td>243.8</td>
<td>11.1</td>
</tr>
<tr>
<td>Ash stands</td>
<td>214.7</td>
<td>2.3</td>
<td>179.8</td>
<td>19.4</td>
</tr>
<tr>
<td>Birch stands</td>
<td>291.9</td>
<td>2.0</td>
<td>237.7</td>
<td>22.8</td>
</tr>
<tr>
<td>Black alder stands</td>
<td>269.1</td>
<td>2.1</td>
<td>305.9</td>
<td>-12.0</td>
</tr>
<tr>
<td>Aspen stands</td>
<td>298.0</td>
<td>2.0</td>
<td>291.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Grey alder stands</td>
<td>223.2</td>
<td>2.3</td>
<td>170.6</td>
<td>30.8</td>
</tr>
</tbody>
</table>
Relative standard error remains similar (about 2%) in all cases applying kNN method and satellite images, when the estimated object is smaller than mature stands of the whole forest enterprise. Having estimated growing stock volume only according to the data of field measured sample plots (conventional method) – errors increase by 2-3 times. The estimated volume per 1 ha differs by up to 10% (Fig. 8).

**Fig 8.** Volumes per 1 ha and relative standard accuracies achieved for different area units using different approaches of sampling based inventories of mature forests: a) volume per ha estimated by forest districts b) relative standard error estimated by forest districts c) volume per ha by field measured sample plots (conventional method) d) relative standard error by forest inventory engineers of the (LFIMI) e) volume per ha by prevailing tree species f) relative standard error by prevailing tree species

**The use of medium resolution satellite images for the estimation of growing stock volume at a forest compartment level**

Assessing prediction accuracy of the growing stock volume of a forest compartment, the main focus was on the possibilities to estimate growing stock volume of a forest compartment by methods described in the work. It was assumed that growing stock volume determined during stand-wise forest inventory could not be used as the standard.
At the same time it was assessed whether the position of plots in the forest has influence on the volume estimation accuracy on compartment level. It was found that mean square deviation (31.9) is obtained by 4-12 % higher if the calculations are based on sample plots which occurred not only within mature and over mature, but also within all other stands. Mean growing stock volume per 1 ha on all 19 final felling areas comprised 422 m³/ha, i.e. by 10 %, while total growing stock volume -11337 m³, i.e. by 15 % higher than the ascertained by field measurements in cutting areas, if all 2nd phase sample plots were used.

Due to a small number of 2nd phase sample plots (190), further studies concentrated on results obtained using sample plots measured in all, not only mature or over mature stands.

Summarized results of 19 final felling areas are provided in Table 4. We found that mean growing stock volume of a stand per 1 ha was reduced (-0.7 – -2.6%) in comparison to the mean volume per 1 ha ascertained for final felling areas, when kNN and MSN methods with 10 closest or the most similar neighbours (further called kNN10 and MSN10) were used. The difference of mean volume per 1 ha from the field-measured one comprised only 0.3-0.5 %, using MSN method with one the most similar neighbour (further called MSN1 method). The lowest mean square deviation of 27.9 % was obtained by kNN method. Mean square deviation of the growing stock volume of a stand was obtained similar also by MSN10 method (28.0 %). Mean square deviation obtained by MSN1 method was by 1-2% higher than the one obtained by kNN10 method. The total volume of all final felling areas in the study, obtained having chosen the best (the least errors are obtained) method ( kNN10) and using sample plots located in the whole stand, was by 5 % higher than the volume determined for final felling areas (9373 m³).

**Table 4. Validation statistics for 19 final felling areas**

<table>
<thead>
<tr>
<th>Extraction of X-variables</th>
<th>Field plots used</th>
<th>Schemes of virtual sample point distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30x30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D_T</td>
</tr>
<tr>
<td>X_NN</td>
<td>Y_ALL</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Y_M</td>
<td>28.1</td>
</tr>
<tr>
<td>X_BIL</td>
<td>Y_ALL</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>Y_M</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X_NN</td>
<td>Y_ALL</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Y_M</td>
<td>26.8</td>
</tr>
<tr>
<td>X_BIL</td>
<td>Y_ALL</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Y_M</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X_NN</td>
<td>Y_ALL</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Y_M</td>
<td>27.4</td>
</tr>
<tr>
<td>X_BIL</td>
<td>Y_ALL</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>Y_M</td>
<td>25.0</td>
</tr>
</tbody>
</table>

21
Densification of 'virtual sample points' has an insignificantly (by about 1%) reduced mean square deviation from the error obtained under 30x30 m density of the 1st phase sample units, thus it can be said that accuracy is not affected by the density of the grid. The obtained results are practically unaffected by the extraction methods of auxiliary information values (X variables), i.e. the closest neighbour or bilinear interpolation, as mean square deviation differed by 0.3 – 4.8% depending on the value extraction method.

Growing stock volume of individual forest compartments (in this case final felling areas), when the best method (kNN10) is applied, was estimated with 27-28% accuracy, expressed by mean square deviation. Only in 7 final felling areas out of 19 used in the study the predicted volume differed by less than 10%, while in 11 - by less than 20% from the field – measured volume.

Mean square error of growing stock volume estimated for 'virtual sample points' comprises 40-43%, however, such errors could be received both due to the delineation of compartment boundaries, and due to geometric inaccuracies of satellite images. Therefore, spatial autocorrelation analysis was applied. In each 'virtual sample point' stand volume per 1 ha was modelled, finding out volume difference of the predicted volume value and of the volume value of final felling area on which the point occurs. Then peculiarities of the spatial variation of volume difference are elucidated. In all the final felling areas analysed in the study statistical values Moran’s I and Z statistics were estimated. Almost in all cases the probability that spatial distribution of volume differences failed to differ from the random was less than 1%, i.e. volume differences in 'virtual sample points' were autocorrelated in space, while Z statistics decreased with increasing buffer zone, which shows the influence of compartment boundary on the size of error in 'virtual sample point'(Fig. 9)

**Fig. 9.** Statistical significance of a statement that the clustered pattern of volume of growing stock per 1 ha estimation residuals for 30x30 m “virtual samples points” could not be the result of random chance, depending on the buffer distances used to reduce the core area of FFA. The light grey shade indicates the critical values for 0.01 significance level; a) nearest neighbour method was used to extract satellite image band-wise digital number values, b) bilinear interpolation was used to extract satellite image band-wise digital number values.
Having eliminated barely 3 final felling areas with the highest errors, it was found that the modelled volume even for 2/3 of the remaining cutting areas differed by 20% and less from the estimated volume in cutting areas.

**Determination of changes in the forest based on satellite images and using estimation methods on the basis of two-phase sampling**

Grids of the main forest characteristics were created by kNN method and using SPOT Xi images as well as the data of measurements in sample plots. Forest parameters are represented in such grids as a continuous phenomenon.

Applying the proposed algorithm it was achieved that about 69% of areas, classified as potential cutting, were cutting sites or young stands up to 15 yr. of age (Table 5). On the other hand, about 71.4% of cutting sites and young stands up to 15 yr. of age according to the data of stand-wise forest inventory of 2003 were detected by the described here method. The 'user's' accuracy fails to rise independently of the size of forest parameter grid cells: 20x20 m, 10x10 m or 5x5 m. 24.5-31.3% of areas, ascertained as potential cutting, according to the data of forest inventory of 2003 do not fall into the category of cutting areas or young stands. Analysing the location of such areas, it was noticed that these can be stands where non-clear cuttings were performed. Therefore, we took advantage of the GIS database of silvicultural measures carried out from 1988 to 1998. Having discarded areas where cuttings were ascertained by kNN method, and as they were neither a cutting site nor a young stand of 2003, in which improvement cuttings were performed in 1988-1998, the value of the 'error' was reduced by 24-32%.

**Table 5.** Accuracy of forest change detection subtracting grids of a certain forest characteristic based on old stand-wise inventory data and kNN estimates (numerator: area, ha, denominator: first number – ‘user’s accuracy’, second number – ‘producer’s accuracy’)

<table>
<thead>
<tr>
<th>Stand-wise forest inventory data from 2003</th>
<th>Clear-cut area or stand under 15 years</th>
<th>Other</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume per 1ha, grid cell size 20x20 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated</td>
<td>Potential cutting</td>
<td>441.28 ha</td>
<td>201.00 ha</td>
</tr>
<tr>
<td></td>
<td>(68.7%; 71.4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No change</td>
<td>176.72 ha</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>618.00 ha</td>
<td></td>
</tr>
<tr>
<td>Volume per 1ha, grid cell size 10x10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated</td>
<td>Potential cutting</td>
<td>462.32 ha</td>
<td>277.19 ha</td>
</tr>
<tr>
<td></td>
<td>(62.5%; 74.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No change</td>
<td>158.22 ha</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>620.54 ha</td>
<td></td>
</tr>
<tr>
<td>Volume per 1ha, grid cell size 5x5 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated</td>
<td>Potential cutting</td>
<td>456.44 ha</td>
<td>294.78 ha</td>
</tr>
<tr>
<td></td>
<td>(60.7%; 73.6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No change</td>
<td>163.38 ha</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>619.82 ha</td>
<td></td>
</tr>
</tbody>
</table>
Overall identification accuracy obtained in the study is not very high, therefore, solutions of additional processing of the obtained change grids were suggested and adapted.

Detection accuracy of changes in the forest comprises about 90% independently of the applied geographic grid manipulation method (MINAREA or EROSREC) (Table 6). $k$ statistics, showing difference between the attainable accuracy and accuracy which would be obtained by randomly classifying the analysed area, was obtained about 0.67, i.e. changes in the forest were determined by 67% better than random classification. The statistics $k$ improves from 0.67, when 4 cell groups are eliminated, up to 0.71, when 13 groups of cells are eliminated, classified as the change.

**Table 6.** Accuracies of forest change detection after geographic manipulation techniques were used

| Number of cells used for manipulation settings | Manipulation technique: MINAREA | | | 
|-----------|-----------------------------|---|---|---|
| | Producer’s | User’s | Overall | $k$ statistic |
| 4 | 88.81 | 60.67 | 91.39 | 0.67 |
| 5 | 88.73 | 61.56 | 91.65 | 0.68 |
| 6 | 88.66 | 62.38 | 91.89 | 0.69 |
| 7 | 88.66 | 63.34 | 92.16 | 0.69 |
| 8 | 88.56 | 64.04 | 92.34 | 0.70 |
| 9 | 88.56 | 64.56 | 92.48 | 0.70 |
| 10 | 88.56 | 64.83 | 92.56 | 0.71 |
| 11 | 88.33 | 65.12 | 92.62 | 0.71 |
| 12 | 88.30 | 65.56 | 92.73 | 0.71 |
| 13 | 88.18 | 65.89 | 92.81 | 0.71 |

| Number of cells used for manipulation settings | Manipulation technique: EROSREC | | | 
|-----------|-----------------------------|---|---|---|
| | Producer’s | User’s | Overall | $k$ statistic |
| 0.5 | 87.84 | 63.62 | 92.19 | 0.69 |
| 1 | 81.59 | 69.52 | 92.56 | 0.70 |
| 1.5 | 78.06 | 75.11 | 93.16 | 0.71 |
| 2 | 71.06 | 83.22 | 90.92 | 0.66 |
| No adjustment | | | 89.11 | 0.61 |

The MINAREA geographic manipulation technique increases the 'user's' accuracy by 12-19%. However, the EROSREC method of results processing resulted in a much higher by 10-20% 'user's' accuracy, as compared to the accuracy obtained by MINAREA technique. The 'producer's' accuracy, having additionally processed the results, is obtained by 18 – 26% higher in comparison to the accuracy obtained detecting changes in the forest without post-processing of results. Overall accuracy and $k$ statistics is obtained by 3-15% lower, if no additional processing of results is applied.
Estimation of wind storm caused damages based on medium resolution satellite images

It is extremely important to find the threshold behind which the difference in the values of satellite images is regarded as an essential shift identifying changes according to the difference of satellite images of two dates. Increasing the limit, the percentage of reliable identification increases until 95-98% is reached. This level is commonly attained when $Y_{TM}$ value reaches 13. Further increasing $Y_{TM}$ value up to 20, the percentage of reliable identification augments insignificantly (Fig. 10). Similar tendencies were observed after estimation by statistics.

![Graphs showing accuracy of classification](image)

Fig. 10. Overall accuracy of classification of wind damaged areas, depending on the percentage of volume actually damaged to be considered as a change and the threshold value of difference image identifying a change: a) pine stands, b) spruce stands, c) deciduous stands.

Table 7 presents a summarized statistics on the loss of the growing stock volume in stands in the whole object, which differs from the volume, ascertained on the GIS database of storm-damaged forest areas. The total volume is estimated by 31 – 45 % lower than the 'true' total volume (Solution 1). Having done calibration (Solution 2), the total modelled volume was obtained by 2.1 – 4.2 % lower than the standard total volume.
Table 7. Total volumes of wind damaged trees in the study area

<table>
<thead>
<tr>
<th>Prevailing species</th>
<th>Number of compartments</th>
<th>Total volume of wind damaged trees, thou. m³</th>
<th>Difference compared to areal photography based inventory data, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Just difference of two satellite images used (Solution 1)</td>
<td>Prediction using kNN and information from satellite images and stand-wise forest inventory (Solution 2)</td>
</tr>
<tr>
<td>Pine</td>
<td>37632</td>
<td>649.0</td>
<td>1153.4</td>
</tr>
<tr>
<td>Spruce</td>
<td>8633</td>
<td>152.3</td>
<td>227.4</td>
</tr>
<tr>
<td>Deciduous</td>
<td>17495</td>
<td>133.6</td>
<td>186.3</td>
</tr>
<tr>
<td>All</td>
<td>63760</td>
<td>934.9</td>
<td>1567.1</td>
</tr>
</tbody>
</table>

CONCLUSIONS AND SUGGESTIONS

Summarizing the study results, the following conclusions are drawn:

1. The most appropriate method by which on the base of medium-resolution satellite images and GIS database information, applying a two-phase sampling scheme, significant for Lithuanian forest inventory parameters are estimated, is the k-nearest neighbour (kNN) method. Having applied the most optimal variant of kNN method, the lowest attained mean square errors of forest parameters estimation on sample plot level comprised 27% of stand mean diameter, 20% of mean height, 40% of basal area, 35% of mean age, 43% of growing stock volume per ha, 33% of the coniferous percentage.

2. No application tactics of the methods based on two-phase sampling was found which would ensure the highest accuracy of all estimated forest characteristics. The settings of methods should be optimized in every concrete case of application in practice.

3. Using medium resolution satellite images and estimation schemes based on two-phase sampling in the inventory of mature stands, a close to 2% accuracy can be attained on the level of a forest district, economic section of a forest enterprise or stand-wise forest inventory object, without essentially increasing the costs.

4. Estimation schemes based on medium resolution satellite images and two-phase sampling fail to ensure sufficient growing stock volume
determination on the level of a separate forest compartment or final felling area; mean square deviation comprised 27% of stand growing stock volume.

5. Medium resolution satellite images and estimation schemes based on two-phase sampling provide preconditions to detect changes in the forest. Clear fellings in the study object were determined with an overall identification accuracy of 90% and by 71% better than the accuracy of random classification, using for that purpose an original algorithm based on the difference of grids of forest parameters created with the help of stand-wise forest inventory data and medium resolution satellite images, corrected taking into account the size and shape of the outline of formed changes. 95% of forest compartments, where clear cuttings were performed, may be detected by identifying that part of the compartment area where essential changes of forest parameters took place.

6. An integrated use of medium resolution satellite images of different dates and stand-wise forest inventory data enables an efficient and reliable assessment of rapid changes in the forest. In the study object, forest areas damaged by wind storm on 8 August 2010 were mapped with 95-98% overall identification accuracy. The total volume of damaged stands was estimated by 2.5% lower than the parameter achieved using interpretation of aerial imagery based orthophoto maps.

We suggest:

1. Estimation schemes based on medium resolution satellite images and two-phase sampling should be implemented in the inventories of mature stands, seeking to statistically reliably estimate the volume of objects smaller than all mature stands of a forest enterprise. This could be done also in those forest enterprises where inventory of mature stands has already been carried out.

2. The use of integrated stand-wise forest inventory data, medium resolution satellite images, estimation schemes based on two-phase sampling should comprise the basis of the system for control of forest cover dynamics. Such a system could be used both for the estimation of annual changes of forest land areas in Lithuania according to intergovernmental guidelines on land use change and forestry activities prepared by the Committee on Climate Change, taking into account the United Nations’ Framework Convention on Climate Change and the Kyoto Protocol requirements for land-use change in forestry sector, ensuring the continuity of Forest State Cadastre and stand-wise forest inventory, as well as cheap and efficient ascertainment of the consequences of natural disasters.

LIST OF PUBLICATIONS

Articles published in journal referred in database of Information Sciences Institute ,ISI Web of Science‘

Articles published in peer-reviewed scientific journals, including international scientific databases


Articles published in other peer-reviewed scientific journals


CURRICULUM VITAE

Name: Donatas Jonikavičius
Date of birth: 9 of November, 1982
Education:
2001-2005 Lithuanian University of Agriculture, Akademija, Kaunas district, Lithuania. BSc in forestry.
2005-2007 Lithuanian University of Agriculture, Akademija, Kaunas district, Lithuania. MSc in forestry.
2007-2012 Aleksandras Stulginskis University, Akademija, Kaunas district, Lithuania. PhD student in Institute of Environment, GIS education and research.

2008-present junior Researcher, Aleksandras Stulginskis University, Akademija, Institute of Environment, GIS education and research centre.

2010-present junior Lecturer Aleksandras Stulginskis University, Faculty of forestry and ecology, Forest management department.

REZIUMĖ

Viena iš svarbiausių miškotvarkos, kaip miško ūkio planavimo sistemos dalių yra miškų inventorizacija. Vykdant miškų inventorizaciją būtina naudoti naujausias ir pažangiausias technologijas bei metodinius sprendimus norint gauti patikimus savalaikius ir kokybiškus duomenis apie miškus. Lietuvos miškų inventorizacijos sistémą sudarančios valstybinė (SMI) bei nacionalinė (NMI), taip pat brandžių medynų (BMI) ir prieškirtimės (PMI) miškų inventorizacijos praktiškai vykdomos nepriklausomai viena nuo kitos, o jų metu surenkami duomenys dar sunkiai yra derinami tarpusavyje. Todėl natūralus yra poreikis tiek tobulinti esamus, tiek kurti naujus sprendimus, kurie įgalintų tikslinti, piginti, greitinti, plėsti šias inventorizacijas, jas jungti į vieną gerai veikiančią inventorizacijos sistemą. Vienas iš būdų tai padaryti gali būti nuotolinio tyrinio tyrimų informacijos naudojimas.

REZIUMĖ

Viena iš svarbiausių miškotvarkos, kaip miško ūkio planavimo sistemos dalių yra miškų inventorizacija. Vykdant miškų inventorizaciją būtina naudoti naujausias ir pažangiausias technologijas bei metodinius sprendimus norint gauti patikimus savalaikius ir kokybiškus duomenis apie miškus. Lietuvos miškų inventorizacijos sistémą sudarančios valstybinė (SMI) bei nacionalinė (NMI), taip pat brandžių medynų (BMI) ir prieškirtimės (PMI) miškų inventorizacijos praktiškai vykdomos nepriklausomai viena nuo kitos, o jų metu surenkami duomenys dar sunkiai yra derinami tarpusavyje. Todėl natūralus yra poreikis tiek tobulinti esamus, tiek kurti naujus sprendimus, kurie įgalintų tikslinti, piginti, greitinti, plėsti šias inventorizacijas, jas jungti į vieną gerai veikiančią inventorizacijos sistemą. Vienas iš būdų tai padaryti gali būti nuotolinio tyrinio tyrimų informacijos naudojimas. Nuotoliniai tyrimai – informacijos apie objektų fizines, chemines ir biologines savybes gavimas be tiesioginio fizinio kontaktos. Šiuo metu nuotolinio tyrinio metodai plačiai taikomi miškų inventorizacijose. Tradiciškai Lietuvoje buvo susiformavus nuomonė, kad miškų inventorizacijoje dėl savo detalumo, vaizdumo, praktinio naudojimo patirties, tradicijų ir t.t. gali būti naudojamos tik aerofotonuotraukos ar aerovaizdų pagrindu sudarytai ortofotoplanai, o kiti nuotoliniai tyrimų duomenų šaltiniai, pavyzdžiui kosminiai vaizdai, yra nepatikimi, netikslūs, per brangūs ir t.t. Dėl šios priežasties vidutinės skiriamosios gebos kosminių vaizdų naudojimas Lietuvos miškų inventorizacijoje yra daugiau mokslinių tyrimų nei praktinio tyrimo metodai, tradicijų ir t.t. gali būti naudojamos tik aerofotonuotraukos ar aerovaizdų pagrindu sudaryti ortofotoplanai, o kiti nuotoliniai tyrimų duomenų šaltiniai, pavyzdžiui kosminiai vaizdai, yra nepatikimi, netikslūs, per brangūs ir t.t. Dėl šios priežasties vidutinės skiriamosios gebos kosminių vaizdų naudojimas Lietuvos miškų inventorizacijoje yra daugiau mokslinių tyrimų nei praktinio tyrimo metodai, tradicijų ir t.t. gali būti naudojamos tik aerofotonuotraukos ar aerovaizdų pagrindu sudaryti ortofotoplanai, o kiti nuotoliniai tyrimų duomenų šaltiniai, pavyzdžiui kosminiai vaizdai, yra nepatikimi, netikslūs, per brangūs ir t.t. Dėl šios priežasties vidutinės skiriamosios gebos kosminių vaizdų naudojimas Lietuvos miškų inventorizacijoje yra daugiau mokslinių tyrimų nei praktinio tyrimo metodai, tradicijų ir t.t. gali būti naudojamos tik aerofotonuotraukos ar aerovaizdų pagrindu sudaryti ortofotoplanai, o kiti nuotoliniai tyrimų duomenų šaltiniai, pavyzdžiui kosminiai vaizdai, yra nepatikimi, netikslūs, per brangūs ir t.t. Dėl šios priežasties visada naudojimas visada yra susijęs su kitokiais metodiniais vaizdų apdorojimo principais nei vizualus aerofotonuotraukų ar skaitmeninių aerovaizdų dešifravimas.


Hipotezė: Optimalaus turinio, tinkamos kokybės, prieinamos kainos nuotolinės tyrimų duomenų derinys, kartu su objektyviais bei efektyviais į
apdorojimo sprendimais šiuo metu sudaro svarbias prielaidas tobulinti miškų inventorizacijos metodus.

**Bendrasis darbo tikslas** – Lietuvoje vykdomų miškų inventorizacijų tobulinimas kosminių nuotolinių tyrimų vaizdų bei GIS duomenų bazių pagrindu.

**Darbo konkretusis tikslas** – ištirti kosminių nuotolinių tyrimų vaizdų ir GIS duomenų bazių informacijos, jos apdorojimo metodų galimybes nustatant įvairias Lietuvos miškų charakteristikas, orientuojantį į įvairias miško inventorizacijos schemas.

**Darbo uždaviniai:**

1. Aptarti kosminių nuotolinių tyrimų vaizdų ir GIS duomenų bazių informacijos naudojimo vertinant įvairias Lietuvos miškų charakteristikas metodines prielaidas.
2. Ištirti dviejų fazių atrankos schemos taikymo vidutinės skiriamosios gebos kosminių vaizdų pagrindu vertinant įvairias Lietuvos miškų charakteristikas metodines prielaidas.
3. Ištirti dviejų fazių atrankos schema grindžiamo vidutinės skiriamosios gebos kosminių vaizdų taikymo sklypinėje, brandžių medynų bei priešskirtinėje miškų inventorizacijose galimybes.
4. Ištirti operatyvaus pakitimų aptikimo miške, naudojant vidutinės skiriamosios gebos kosminius vaizdus, metodinius sprendimus bei jų taikymo Lietuvos sąlygomis ypatumus.

**Mokslinis naujumas**

Išvystytų vidutines skiriamosios gebos kosminių vaizdų ir dviejų fazių atranka grindžiamų vertinimo schemų naudojimo Lietuvos miškų inventorizacijos metodinio pagrindai.

Sklypinės miškų inventorizacijos duomenų naudojimas kaip pagalbinė informacija kartu su vidutinės skiriamosios gebos kosminiais vaizdais dviejų fazių atrankos schemose vertinant miško charakteristikas.

Pasiūlytas originalus algoritmas, grindžiamas taksacinių rodiklių geografinių matricų, sukurtų sklypinės skiriamosios gebos kosminių vaizdų pagrindu, skirtumų, koreguotu atsižvelgiant į suformuojamų pokyčių kontūrų dydį bei formą, kuris naudotinas pakitimams miške aptikti.

Pasiūlytas metodinis sprendimas kosminių vaizdų pagrindu vertinti staigius miško dangos pokyčius.

**Praktinė darbo reikšmė**

Pasiūlytas metodas kuriuo brandžių medynų inventorizacijos metu arėms procentams tikslumą galime pasiekti girininkijos, urėdijos ūkinės
sekcijos ar sklypinės miškų inventorizacijos vykdytojo darbų objekto lygmeniu, esminiai nedidinant kaštų.

Pasitūrytas operatyvaus pakitimų miške aptikimo metodinis sprendimas, kuris gali būti naudojamas miško žemės dangos pokyčiams vertinti, užtikrinti Miškų valstybės kadastro vedimo ir sklypinės miškų inventorizacijos nepertraukiamumą.

**Disertacijos struktūra**


**Aprobacija**

Paskelbta: 1 straipsnis referuojamoje Mokslinės informacijos instituto duomenų bazėje „ISI Web of Science“, 3 straipsniai recenzuojamuose mokslo leidiniuose, 2 straipsniai kituose recenzuojamuose mokslo leidiniuose; skaityti 5 pranešimai tarptautinėse mokslinėse konferencijose.

**Išvados:**

Apibendrinami tyrimų metu gautus rezultatus, darome tokias išvadas:

1. Tinkamiausias metodas, kuriuo vidutinės skiriamosios gebos kosminių vaizdų bei GIS duomenų bazių informacijos pagrindu, taikant dviejų fazių atrankos schemą, nustatomi Lietuvos miškų inventorizacijai reikšmingi rodikliai, yra k-artiniausio kaimyno (kNN) metodas. Pritaikius optimalų kNN metodo taikymo taktikos variantą, mažiausios pasiekto taksacinių rodiklių nustatymo apskaitos plotelio lygmeniu vidutinės kvadratinės paklaidos sudarė 27% medyno vidutinio skersmens, 20% vidutinio aukščio, 40% skerspločių sumos, 35% vidutinio amžiaus, 43% tūrio viename ha, 33% spygliuočių procentų rodiklio.


3. Naudojami vidutinės skiriamosios gebos kosminius vaizdus ir dviejų fazių atranka grindžiamas vertinimo schemas brandžių medynų inventorizacijoje, artimą 2% tikslumą galime pasiekti girininkijos, urėdijos ūkinės sekcių ar sklypinės miškų inventorizacijos vykdytojo darbų objekto lygmeniu, esminiai nedidindami kaštų.

4. Vidutinės skiriamosios gebos kosminiai vaizdai bei dviejų fazių atranka grindžiamos vertinimo schemas neužtikrina pakankamo medyno tūrio nustatymo tikslumo atskiro miško sklypo ar plynam kirtimui paruoštos biržės lygmeniu, vidutinis kvadratinis nuokrypis sudarė 27 % sklypo medyno tūrio.

31
5. Vidutinės skiriamosios gebos kosminiai vaizdai bei dviejų fazių atranka grindžiamos vertinimo schemas sudaro prielaidas pakitimams miške aptikti. Plynų kirtimai tyrimo objekte buvo nustatyti bendru 90% patikimumu bei 71% geriau nei atsitiktinio klasifikavimo tikslumas, tam naudojant originalų algoritną, grindžiamą taksacinių rodiklių geografinių matricų, sukurtų sklypinės miškotvarkos duomenų bei vidutinės skiriamosios gebos kosminų vaizdų pagrindu, skirtumui, koreguotu atsižvelgiant į suformuojamų pokyčių kontūrų dydį bei formą. 95% miško sklypų, kuriuose atlikti plyni kirtimai, gali būti aptinkami nustatant sklypo ploto dalį, kurioje įvyko esminiai taksacinių rodiklių pokyčiai.

6. Integruotas skirtingų gavimo datų vidutinės skiriamosios gebos kosminų vaizdų ir sklypinės miškų inventorizacijos duomenų naudojimas įgalina operatyviai bei patikimai įvertinti staigiai įvykstančius pokyčius miške. Tyrimų objekte 2010 m. rugpjūčio 8 dienos vėjo štormo pažeisti miško plotai kartografuoti 95–98% patikimumu. Bendras išverstų medynų tūris nustatytas 2,5% mažesnis už rodiklį, nustatytą aeronuotrauka grindžiamų fotoplanų dešifruavimo būdu.

Siūlome:

1. Vidutinės skiriamosios gebos kosminiai vaizdai bei dviejų fazių atranka grindžiamos vertinimo schemas turėtų būti diegiamos brandžių medynų inventorizacijose, siekiant statistiškai patikimai nustatyti mažesnių objektų nei visos miškų urėdijos brandūs medynai tūrį. Tai galėtų būti atliekama ir tose miškų urėdijose, kuriose brandžių medynų inventorizacija jau yra atlikta.

2. Integruotu sklypinės miškų inventorizacijos duomenų, vidutinės skiriamosios gebos kosminų vaizdų, dviejų fazių atranka grindžiamų vertinimo schemų naudojimas turėtų sudaryti miškų dangos dinamikos kontrolės sistemos pagrindą. Tokia sistema galėtų būti naudojama tiek nustatant kasmetinius miško žemės plotų pokyčius Lietuvoje pagal Tarpvyriausybinio klimato kaitos komiteto parengtas žemės naudojimo pakeitimo ir miškininkystės veiklų gaires, atsižvelgiant į Jungtinių Tautų bendrosios klimato kaitos konvencijos ir Kioto protokolo reikavimus žemės naudojimo pakeitimo ir miškininkystės sektoriuje, tiek užtikrinant Miškų valstybės kadastro vedimo ir sklypinės miškų inventorizacijos nepереруксамумą, tiek pigiai bei operatyviai nustatant stichinių veiksnių padarinius.