

# Estimation and Use of Continuous Surfaces of Forest Parameters: Options for Lithuanian Forest Inventory

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## Abstract

Deriving of the continuous surfaces of key forest characteristics from satellite images and point-wise field forest estimates is considered in this paper as a general methodological research framework to integrate sampling based and conventional stand-wise inventory systems. Several non-parametric and parametric estimation methods (two-phase sampling with stratification, k-nearest neighbor and regression) and sources of remotely sensed data (SPOT 4 HRVIR, Landsat-5 TM, panchromatic aerial images) together with the information available from stand-wise forest inventories have been studied on a test area in the Dubrava forest in the central part of Lithuania for the accuracy of pixel-level estimates of key forest characteristics. Integration of the information available from satellite images and limited number of field sample plots with the characteristics of forest compartments, derived during the conventional stand-wise inventory, reduced the root mean square errors of estimates of pixel-level forest characteristics by 9-41%. The idea to convert forest reflectance in the satellite image into the continuous surfaces of forest parameters and use such surfaces to construct spatial units corresponding to conventional forest compartments is discussed as well. The relative efficiency of segmentation, expressed by the minimization of variance of key characteristics within the forest block via delineation of compartments, improves by 13-33% if the continuous surfaces of forest parameters are used instead of original satellite image as an input.

**Key words:** forest inventory, satellite images, pixel-level forest characteristics, two-phase sampling, k-nearest neighbour, regression, segmentation

## Introduction

Lithuanian forest inventory practices can be divided into three broad approaches – stand-wise inventory, National forest inventory by sampling methods and pre-harvesting inventory of forest compartment (Kuliešis 2008). Stand-wise inventory is a main source of information for tactical and operational management planning at a forest estate or forest enterprise level while the National forest inventory covers forests of the country and supports strategic planning. Pre-harvesting inventory usually takes place 1-2 years before the forest compartment is harvested. Stand-wise inventory provides much localized data; it is most often based on subjective visual interpretation of aerial photographs and limited field measurements. Aggregates for large areas are quite often biased (Kuliešis 1999, 2008), especially having in mind the practice inherited from the soviet times to reduce artificially stand volumes. Sampling-based forest inventory provides statistically validated data on numerous forest parameters for large areas, but it fails at local level

(Tokola *et al.* 1996, Kuliešis 1999, Katila and Tomppo 2001). Stand-wise forest inventory used to be the only source of data for all types of forest management planning in Lithuania a decade ago. To date, just a subtle combination of all forest inventory techniques guarantees operative provision of required forest resource information at lowest cost (Kuliešis 2008). Although all types of inventories are aiming at different objectives and utilizing rather different techniques, remote sensing based solutions are discussed in this paper as an essential integrating chain between the inventory approaches.

Modern science and technology theoretically allows every single tree, its location and descriptive characteristics to be measured and stored in a digital database, but there is rather no operational use of that information today. Stand-wise forest inventories define discrete spatial objects with crisp boundaries – forest compartments – and assign uniform characteristics, which are most frequently visually estimated, for all locations inside the polygon. However, natural phenomena usually exhibit both continuous and dis-

crete behavior (Burrough 1996), *e.g.* spatially continuous soil fertility features and abrupt vegetation changes due to some natural or anthropogenic impacts. Such spatial continuity (even interfered by abrupt changes) is rather difficult to visualize using discrete model or choropleth presentations, as mentioned above. Consistently, any forest characteristic of a certain location may be represented using the model of point- or pixel-level forest characteristics. The approach to use continuous surfaces of forest attributes has been used by many countries in their National forest inventories by sampling methods (*e.g.* Tomppo 1993, Nilsson 1997, Tomppo *et al.* 1999, Gjertsen *et al.* 2000, Franco-Lopez *et al.* 2001 and many other authors). It is used to aggregate detailed stand-wise forest information to be represented at more coarse scales (*e.g.* Kurlavičius *et al.* 2004) or when the information at a more detailed level is not available (Päivinen *et al.* 2001). Deriving of the continuous surfaces from point-wise field forest estimates and satellite images is considered to be a general methodological research framework and is expected to be a chain integrating both National forest inventory by sampling methods and conventional stand-wise inventory systems, while pre-harvesting inventory is left outside the scope of the present study.

There are several ways to provide any point (or pixel of a raster) within certain area of interest with forest characteristics: (i) to measure them in the field (Gunnarsson *et al.* 1999), however this is rather expensive, (ii) to measure at some subset in the field and spread-out for other locations using geostatistical methods, *e.g.* kriging interpolation (Gunnarsson *et al.* 1999), but some spatial autocorrelation should be present in the phenomenon under investigation, (iii) to measure *e.g.* on aerial images using stereo photogrammetric equipment, (iv) to use any auxiliary information that correlates with forest characteristics – satellite and aerial images, historical forest inventory information, GIS databases. To date, laser scanning is getting an operational solution to obtain pixel-level forest characteristics, too. Our research focus has been on the fourth approach. Numerous parametric and nonparametric estimations, GIS analysis are used to relate the auxiliary information, available for every location with the actual forest characteristics, measured just for some field samples: regression (*e.g.* Hagner 1990, Nilsson 1997, Mozgeris and Augustaitis 1999), static and dynamic stratification (*e.g.* Poso *et al.* 1987, Mozgeris 1996), k-nearest neighbour estimation (*e.g.* Tomppo 1993, Gjersten *et al.* 2000, Tokola *et al.* 1996), GIS-driven pseudo-raster transformations (Kurlavičius *et al.* 2004).

The nonparametric estimation techniques (numbers and location of field sample plots, detailed set-

tings of two-phase sampling with stratification and k-nearest neighbour, *etc.*) have been well studied by other authors (Tomppo 1993, Tokola *et al.* 1997, Nilsson 1997, Katila and Tomppo 2001, Franco-Lopez *et al.* 2001) and, up to some extent, in our previous research (Mozgeris 1996, Mozgeris 2000, Mozgeris and Jonikavičius 2007). It is well established that the best tactics for using non-parametric estimation methods is impossible to define in advance (Katila and Tomppo 2001). Our own conclusion has been that the quality of auxiliary data is of main importance for the estimation accuracy, while the implementation tactics, estimators (for sure, if the settings are appropriate) play just a secondary role. The approach becomes to find optimal settings for every particular case by testing all possible alternatives. *E.g.* Finnish researchers developed an improved k-nearest neighbour estimator by using special optimization method, called genetic algorithm (Tomppo and Halme 2004). It is well established that any digital map, no matter whether it is land use, land cover or soil map, may improve the accuracy of pixel-level estimations, too (Tokola and Heikkilä, 1997, Katila and Tomppo 2001, Tomppo and Halme, 2004).

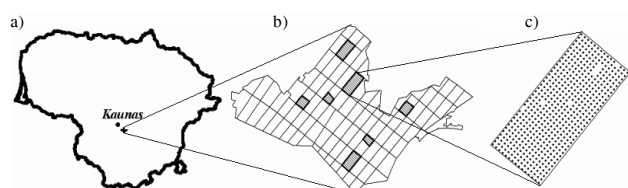
Even the model of pixel-level forest characteristics has proven its usability for numerous sampling-based forest inventory applications, the operational forest management planning approaches require some discretisation of continuous surfaces into areal units, corresponding to forest compartments. Based on the estimated values of certain characteristics points, pixels, *etc.* can be easily grouped to form discrete units. Such an idea has been discussed by Swedish scientists (Holmgren and Thuresson 1997, Gunnarsson *et al.* 1999), however it has not received very much attention in the forest inventory literature so far. Classical image classification algorithms, such as maximum likelihood, parallelepiped or minimum distance, which have been successful for many other applications, have usually limited value for stand-wise forest inventories as regards the delineation of compartments, too. Large approximations are required to express forest characteristics, which are more or less continuous, by few discrete classes. There are a lot of references on using segmentation to divide the remotely sensed image into spatially contiguous regions that are homogeneous regarding their radiometric characteristics (Tomppo 1987, Tomppo 1988, Hagner 1990, Hame 1991, Parmes 1993, Olsson 1994, Haapanen and Pekkarinen 2000). Similar research was carried out in Lithuania a decade ago; however, the results were not operationally used (Mozgeris *et al.* 2000, Mozgeris 2001).

The aims of our study are the following: (i) to test whether the information, available from conventional

stand-wise inventories and used as a source of auxiliary data in addition to satellite images, improves the accuracy of pixel-level estimates and (ii) to test the assumption that the estimation of forest parameters for every pixel of satellite image using, for instance, k-nearest neighbour estimator and ground truth from some sampling-based inventory, and utilizing them instead of original image values – improves the efficiency of segmentation (or delineation of compartments, if the terminology of stand-wise inventory is used).

**Material and methods**

The test area (the Dubrava forest) is located in the central part of Lithuania (24°4'E and 54°50'N) – Figure 1. The forest occupies around 4500 ha, and nearly all Lithuanian forest conditions are present there. A total of 1945 angle count field sample plots (scale factor 2) were established in the forest on 7 forest blocks following 35x35 m sampling scheme (8 plots per 1 ha) in 1999. Coordinates of each plot center were GPS measured using Trimble Pathfinder Pro XRS receiver with accuracies of 2 m. Forest stand and tree param-



**Figure 1.** The location of the Dubrava forest (a), the distribution of test blocks within the forest (b) and the location of sample plots (c)

ters were measured on these plots following the methodology of Lithuanian National forest inventory (Kuliešis and Kasperavičius 1999). The following characteristics were calculated for each story and stand in total: shares of tree species, mean ages, diameters and heights, basal areas, volumes per ha. The mean forest characteristics on the sampled forest blocks are compiled in Table 1. The growing stock volume shares of tree species were: 42% of pine, 29% of spruce, 17% of birch, 9% of oak, 2% of aspen, 1% of black alder and 1% of other tree species.

**Table 1.** Forest characteristics of stands of the sampled forest blocks

Forest characteristic	Mean value	Standard deviation
Mean diameter, cm	28.77	8.55
Basal area, m <sup>2</sup>	23.67	9.88
Mean height, m	24.41	5.26
Mean age, years	67.49	26.63
Volume per 1 ha, m <sup>3</sup>	279.69	136.33
Share of coniferous trees, %	70.14	32.95

The following remotely sensed images and GIS layers were made available for the study:

1.SPOT 4 HRVIR scene from 01.08.1999, scene ID 078/238.

2.Landsat-5 TM scene from 25.08.1987, scene ID 187/022.

3.Panchromatic aerial images, used to produce Lithuanian orthophotographic map ORT10LT, grabbed 07.09.1998 on Kodak Double-X aerial film using Leica RC30 aerial camera and nominal 1:30000 flying altitude. Pixel size of images is 0.45x0.45 m.

4.Boundaries of forest compartments and tabular stand descriptions (from (i) conventional stand-wise inventory, carried-out in 1989, to be used as an auxiliary data source, not updated and (ii) from the year 2000, to be used to validate the segmentations).

Satellite images were processed to the geocoded products using ground control points measured on topographic maps and in the field, stored in Lithuanian coordinate system LKS94. Landsat-5 TM images were re-sampled to the 20x20 m pixel size using nearest neighbour re-sampling technique. All bands of satellite images were used in subsequent analyses except for the thermal band (6) of Landsat-5 TM. Satellite image values were transformed into principal components using correlation matrix. Georeferencing of satellite images was adjusted to improve registration accuracies for the test area using maximum correlation between the first principal component and volume per 1 ha on all sample plots. Somewhat similar approach was successfully used by Poso *et al.* 1987 to adjust the geo-referencing accuracies of sample plots. Average values and standard deviations of original aerial images were calculated for a pixel size 20x20 m to be used later together with satellite images. All maps were digitized and transferred to GIS database.

Although both field measured forest characteristics and auxiliary data, such as satellite or aerial image values, stand-wise inventory attributes, were available for all sample plots, they were randomly divided into two parts during the estimations: the 1<sup>st</sup> phase units and the 2<sup>nd</sup> phase units. It was assumed, that only auxiliary data were available for the 1<sup>st</sup> phase units and both auxiliary and field measured data – for the 2<sup>nd</sup> phase units. Two estimates of pixel-level accuracies were used – the root mean square error (RMSE) and correlation coefficient between estimated and field measured forest characteristics on the 1<sup>st</sup> phase units.

Three estimators were tested to get the continuous surfaces of the main forest parameters from field sample measurements using various sources of auxiliary information: (i) two-phase sampling with stratification (Poso *et al.* 1987), (ii) the k-nearest neighbours (Tomppo 1993), and (iii) regression:

1. All field sample plots were stratified into 20 strata, including both 1<sup>st</sup> phase and 200 randomly selected 2<sup>nd</sup> phase units. Euclidean distance in feature space of auxiliary information was used as the classification criterion. Each 1<sup>st</sup> phase unit was supplied with the average forest characteristic values measured on the 2<sup>nd</sup> phase units, belonging to the same stratum.

2. The forest characteristic for the 1<sup>st</sup> phase unit was calculated as the average value of 5 nearest 2<sup>nd</sup> phase units in feature space of auxiliary information using Euclidean distance. No distance weights were applied for the study.

3. Multiple regression equations were created on the 2<sup>nd</sup> phase units using the values of auxiliary information as independent variables. Later, these models were used to calculate forest characteristics on the 1<sup>st</sup> phase units.

Independent estimates were weighted to get the final estimate:

$$\hat{y} = \sum w_k \hat{y}_{ki} \quad (1)$$

where  $\hat{y}$  - final estimate at point  $i$ ;  $w_k$  - relative weight of an estimate using method  $k$ ;  $\hat{y}_{ki}$  - estimate at point  $i$  achieved using method  $k$ .

Three methods to estimate the weights were used:

1. Inverse values of root mean square errors (*RMSE*) of independent estimates (hereafter Weighting 1):

$$w_k = (1/RMSE_k) / (\sum 1/RMSE_m) \quad (2)$$

where  $m$  indicates the method of image processing, e.g. (1..3).

2. Same as above, but *RMSE* was reduced by value  $C$ , which amounted to 15% of the *RMSE*, assuming that actual value of the *RMSE* might be slightly increased because of random variation in field data (Poso *et al.* 1999) – Weighting 2:

$$w_k = (1/RMSE_k - C) / (\sum 1/RMSE_m - C) \quad (3)$$

3. Squared correlation coefficient between true and estimated field values on the 1<sup>st</sup> phase plots – Weighting 3:

$$w_k = R^2_k / \sum R^2_m \quad (4)$$

To test whether the boundaries of forest compartments and their numerous attributes may improve the accuracy of pixel-level forest estimates, we used the stand-wise forest inventory data from the year 1989, simulating the situation when one might use the information from previous inventories (carried out 10 years or more ago). Attributes of forest compartments

were assigned to all sample plots using standard GIS “point-in-polygon” overlays. Correlation coefficients between corresponding field measured and computed in such a way plot characteristics were calculated. To get the final forest characteristic for the 1<sup>st</sup> phase plots, we combined the estimates by all three types of estimators and SPOT image with the ones, extracted from the descriptions of compartments via the 3<sup>rd</sup> type of weighting (Formula 4). Additionally,  $k$ -nearest neighbour estimator was run with SPOT data alone on pre-stratified field sample plots. “Pre-stratification” means here that the sample plots were divided into two categories on the base of stand-wise data: “forested” and “non-forested” land – only “forested” plots were used for the estimations.

For the image segmentation we used so called “ $t$ -ratio segmentation”, which is a type of region-merging algorithm (Hagner 1990). It can use any original or pre-segmented image as an input and runs by merging adjacent segments if they are similar enough in  $t$ -ratio. Three different approaches to get the segments (boundaries of forest compartments) were tested:

1. Segmentation of original SPOT 4 HRVIR image. Minimal size of segments was set to be 5 pixels (or 0.2 ha in the field), and the value of  $t$ -ratio = 1.

2. Estimation of pixel-level forest parameters for every pixel of satellite imagery and their use in segmentation instead of original image values. The  $k$ -nearest neighbour estimator (see above for detailed settings) and SPOT image were used to get surfaces of height, basal area, age, volume per 1 ha and share of coniferous trees in tree species composition. All the surfaces were combined in a 5-band image and segmented using the same settings as with original SPOT image.

3. Conventional human interpretation of aerial photographs followed by field visits, as used in Lithuanian stand-wise forest inventory. The field inventory was carried out in 2000 by forest inventory engineers of the Lithuanian forest inventory and management planning institute within the frames of special annual training course (Kuliešis and Mozgeris 2003).

To estimate the efficiency of segmentation or division of the forest block into compartments, the following assumptions were used (Kuliešis *et al.* 2003):

1. The variance for every forest characteristic within a forest block may be estimated using the data available from sample plots.

2. The variance for every forest characteristic within a forest compartment or segment and total sum for all compartments or segments within a block may be estimated in the same way, too.

3. The ratio of such variances indicates the efficiency of delineation or segmentation, as the objective of stand-wise inventory is to minimize the with-

in-compartment variance of selected forest characteristics having their sizes at some minimal and mean levels.

The relative efficiency of block division into the compartments or segments for each key forest parameter is found as a ratio:

$$E = 1 - \frac{\sum_{j=1}^k \sigma_{xj}^2 \times n_j}{\sigma_x^2 \times n} \quad (5)$$

where  $\sigma_{xj}^2$  - variance of parameter  $x$  within segment-compartment  $j$ ,  $n_j$  - number of plots within segment-compartment  $j$ ,  $n$  - total number of plots within forest block,  $\sum_{j=1}^k n_j = n$ ,  $\sigma_x^2$  - variance of parameter  $x$  within forest block.

Higher value of  $E$  (maximal value 1) indicates more efficient delineation of compartments.

Conventional GIS and remote sensing packages (Arc/Info, ArcView and ERDAS Imagine, PCI Geomatics) were used to perform GIS processing tasks, working with satellite and aerial images. Non-standard software used for the research was the SMI system developed at Helsinki University (two-phase sampling with stratification,  $k$ -nearest neighbour), SkoGIS software, developed at the Remote Sensing laboratory at

Swedish university of Agricultural Science in Umeå (segmentation of images), as well as some own tools.

### Results

The pixel-level accuracies achieved using different estimation techniques and input remotely sensed images are summarized in Table 2. SPOT images yielded in better accuracies for all forest characteristics – the root mean square errors were by 9-41% smaller than using other types of remotely sensed information. Nevertheless, combination of the estimates achieved using Landsat and aerial images with the ones based on SPOT, resulted in lowest root mean square errors if the squared correlation coefficient (or coefficient of determination, denominator in Table 2) between true and estimated field values on test sample plots was used as a weight (except for the regression estimation). The decrease in root mean square error was up to 5%. Other two weighting techniques did not improve the estimates achieved using just SPOT images as the auxiliary data. We got root mean square errors that made up 29% of mean diameter on all sample plots of the research object, 39% was the figure for basal area, 23% for height, 37% for age, 45% for volume per ha and 34% for the share of coniferous trees in tree species composition of the stand, if the most accurate estimation technique was used.

**Table 2.** Achieved pixel-level accuracies using different remotely sensed images, estimators and estimation tactics (numerator – root mean square errors, denominator - correlation coefficients between the estimated and field measured forest characteristics on the 1<sup>st</sup> phase units)

Source information / weighting method	Diameter, cm	Basal area, m <sup>2</sup>	Height, m	Age, years	Volume per 1 ha, m <sup>3</sup>	Share of coniferous trees, %
<b>Two-phase sampling with stratification</b>						
Landsat TM	10.49/0.306	11.22/0.061	7.62/0.282	28.76/0.318	146.42/0.204	30.07/0.448
Spot Xi	8.53/0.635	9.72/0.492	5.59/0.702	26.40/0.497	128.01/0.519	25.48/0.645
Aerial image	10.61/0.329	10.62/0.305	7.40/0.389	29.84/0.239	143.24/0.298	32.92/0.225
Weighting 1	8.86/0.641	9.80/0.481	5.99/0.696	26.31/0.549	129.33/0.528	25.80/0.648
Weighting 2	8.84/0.641	9.79/0.481	5.96/0.696	26.29/0.549	129.23/0.528	25.74/0.648
Weighting 3	8.46/0.650	9.54/0.501	5.62/0.709	25.75/0.546	126.13/0.531	24.71/0.667
<b><math>k</math>-nearest neighbor</b>						
Landsat TM	11.21/0.237	11.5/0.099	8.14/0.193	29.62/0.334	151.37/0.203	28.79/0.506
Spot Xi	8.53/0.630	9.90/0.475	5.74/0.683	26.00/0.523	130.59/0.506	25.22/0.654
Aerial image	11.23/0.214	11.11/0.229	7.84/0.279	31.85/0.135	151.91/0.203	34.06/0.181
Weighting 1	9.02/0.610	9.76/0.473	6.24/0.661	25.72/0.543	129.28/0.513	24.93/0.66
Weighting 2	8.99/0.613	9.75/0.475	6.20/0.665	25.68/0.544	129.14/0.515	24.86/0.662
Weighting 3	8.44/0.640	9.56/0.496	5.72/0.688	24.78/0.566	126.02/0.528	23.94/0.679
<b>Regression</b>						
Landsat TM	10.57/0.274	11.22/0.140	7.60/0.256	29.03/0.256	150.08/0.209	28.22/0.537
Spot Xi	8.84/0.596	9.29/0.554	5.78/0.678	26.12/0.502	130.29/0.518	24.79/0.665
Aerial image	10.52/0.293	10.79/0.255	7.46/0.319	29.39/0.217	147.71/0.239	32.81/0.139
Weighting 1	9.34/0.575	9.91/0.516	6.32/0.647	26.82/0.483	135.74/0.501	25.73/0.677
Weighting 2	9.33/0.576	9.90/0.518	6.30/0.649	26.80/0.484	135.62/0.502	25.67/0.678
Weighting 3	8.90/0.595	9.38/0.551	5.86/0.673	26.01/0.505	130.69/0.522	24.53/0.680

If the information from stand-wise forest inventory was used in addition to SPOT image as an auxiliary data source, the estimation root mean square error decreased by 14-33% for all forest variables and all types of estimators, compared to the case if SPOT image alone was used (Figure 2). Estimation accuracies did improve if the stand-wise forest inventory information was used just to pre-stratify the sample plots into two broad categories – “forested” and “non-forested”, to leave out such forest land categories, used in Lithuanian forest inventory, as young forest with unclosed canopy layer, clear cuts, etc. k-nearest neighbour estimator applied with the SPOT images for “forested” sample plots only decreased the root mean square errors by 3-10%.

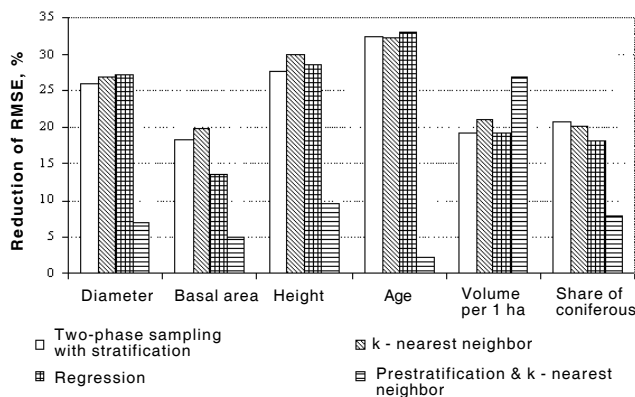


Figure 2. Reductions of root mean square errors in estimates of pixel-level key forest characteristics if information from stand-wise inventories was used in addition to SPOT image

The relative efficiency of automatic delineation of discrete spatial units, corresponding to forest compartments was found to improve by 13-33% when forest characteristics for every pixel of satellite image were estimated and used instead of reflectance-based values of satellite images (Figure 3). However, none of remote sensing aided technique managed to compete with human interpretation of aerial photographs fol-

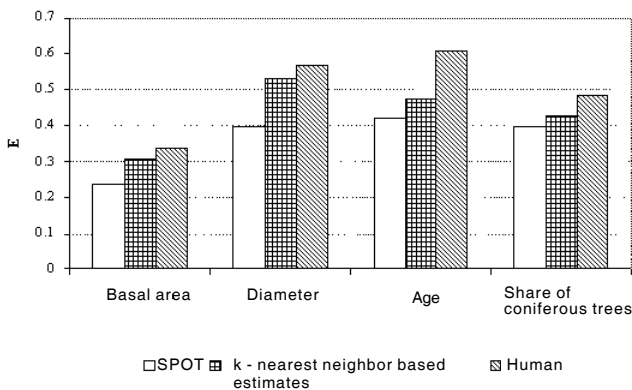


Figure 3. The relative effectiveness of singling-out forest compartments using different techniques

lowed by field visits – here the reduction of variance of key forest attributes by singling-out compartments was higher by 7-28% than the best achieved result utilizing SPOT images.

### Discussion and conclusions

The root mean square errors achieved in this research still may look rather high for practical foresters with long stand-wise forest inventory experience. However, they refer to point- or pixel-level locations and not the stands and are in full agreement with the findings of other researchers (e.g. Poso *et al.* 1999, Franco-Lopez *et al.* 2001, Katila and Tomppo 2001). Different types of remotely sensed images resulted in rather different outcomes in our research. Poso *et al.* 1999 reports more similar results with different sources of auxiliary information. Landsat images, used in our study, were acquired 12 years before the field survey took place. Panchromatic images most likely suffer here from limited spectrum. So, they are potentially of poorer quality as SPOT images. Weighting of alternative estimates always resulted in improved final results in the above mentioned Finnish research (Poso *et al.* 1999), with the estimation root mean square error used as the weight. We get improved results just with the squared correlation coefficient (or coefficient of determination) between true and estimated field values on test sample plots. This weighting approach has already been used to integrate different bands of satellite images several decades ago (Tomppo 1987) and logically relates with the variance of parameters, giving higher weights for more accurate independent estimates.

Auxiliary information that correlates with forest characteristics and is easily available is a potential candidate to be used in development of continuous surfaces of pixel-level forest estimates (Poso *et al.* 1990, Poso *et al.* 1999). Our assumption has been that the boundaries of forest compartments and their attributes, captured within the frames of conventional stand-wise inventories and stored in digital database for all forest of Lithuania no matter their ownership structure and management regimes, are a potential source of such auxiliary information. They always improved the estimation accuracies. Attributes of forest compartments were integrated with the satellite images via principal component transformations in another our research (Mozgeris and Jonikavičius 2007), resulting in improved pixel-level accuracies of estimates. Poso *et al.* 1999 reported the improved estimation accuracies with the use of compartment data in Finland, too.

Improved delineation of compartments is possible when forest reflectance in the satellite image is converted into the multi-layer grids of forest parameters. For-

est characteristics inside the compartment should be as homogeneous as possible while they should differ from other compartments as much as possible (Orlov 1927). To delineate forest into compartments several forest characteristics are used: tree species composition, basal area, age, diameter, site type, etc. The best delineation of a forest block into compartments is usually achieved when the variance of forest parameters within a block is maximal (Kuliešis *et al.* 2003). Converting forest reflectance stored originally in the satellite images into the forest parameters brings their domain closer to the real conditions operated in forest inventories. In addition to the increased amount of information, estimated surfaces of forest parameters are based on actual field measured characteristics, influencing the improved segmentation efficiencies.

Improved efficiency of segmentation was illustrated here using only SPOT image and k-nearest neighbor estimator. Segmentation of both SPOT and Landsat data (Mozgeris 2001) resulted in efficiencies compatible with the human delineation of compartments as regards the diameter and age. The efficiencies were lower than achieved with the estimated surfaces for basal area and the percentage of coniferous tree species. However, the segmentation was guided by updated borders of compartments from 1989 year stand-wise inventory. Borders of compartments were updated using aerial images from 1998 – the main idea of that study was that minor human intervention (editing the borders of non-forest and not-forested, clear-cut, forest regeneration areas) together with the use of medium resolution and low cost satellite images and forest compartment data stored in GIS would facilitate stand-wise forest inventory. It is very likely there are numerous solutions to improve the segmentation results, however our aim in this paper is just to test basic idea – do we achieve better results replacing reflectance values of satellite image with forest parameters, thus we avoid further discussion on simultaneous use different satellite images or segmentation tactics.

Looking forward in to the future, the borders of segments, not illustrated here, are of limited semantic value and difficult to utilize for conventional forest mapping on a scale of 1:10000. However, the information collected for every forest compartment in Lithuania within the frames of stand-wise forest inventories is stored in a GIS database – the stand-wise forest inventory at present involves practically updating of available information (Brukas *et al.* 2000, Mozgeris *et al.* 2008). So, there may be numerous applications of approaches discussed in this paper, e.g. to segment the surfaces of forest characteristics developed in manner of Finnish multi-source national forest inventory (Tomppo 1993), to guide the segmentation with

the borders of forest compartments and to use the results to identify the changes/inaccuracies in stand-wise data, thus leading towards bridging gaps between two major Lithuanian forest inventory systems.

The main conclusions of the research described in this paper are:

1. Integration of the information available from satellite images and limited number of field sample plots with the characteristics of forest compartments, derived during the conventional stand-wise inventory, improved the accuracy of estimation of pixel-level forest characteristics.

2. Effectiveness of segmentation, aimed to construct spatial units corresponding to conventional forest compartments, improved when forest reflectance in the satellite images were converted into the continuous surfaces of key forest parameters.

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## ОБРАЗОВАНИЕ И ИСПОЛЬЗОВАНИЕ НЕПРЕРЫВНЫХ ПОВЕРХНОСТЕЙ ЛЕСНЫХ ХАРАКТЕРИСТИК: ВОЗМОЖНОСТИ ДЛЯ ЛЕСНОЙ ИНВЕНТАРИЗАЦИИ В ЛИТВЕ

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*Резюме*

Использование непрерывных поверхностей основных лесных характеристик, установленных на основе космических изображений и данных полевых пробных площадей рассматривается в настоящей статье как основной методический подход исследований, направленных на сближение систем лесной инвентаризации в Литве – Национальной лесной инвентаризации выборочными методами и традиционной выделной инвентаризации. Точность оценки ключевых лесных характеристик на уровне ячейки растрового изображения определялась на специальном полигоне исследований, созданном в Дубравском лесу (центральная часть Литвы), используя разные непараметрические и параметрические методы оценки (двух-фазовый отбор, к-ближний соседний и регрессия), данные дистанционного зондирования (SPOT 4 HRVIR, Landsat-5 TM и панхроматические аэроизображения) и информацию выделной инвентаризации леса. Установлено, что совместное использование космических изображений, полевых данных учетных площадей с показателями таксационных выделов, установленных в рамках повыделной инвентаризации леса, позволило уменьшить среднеквадратические ошибки лесных характеристик на уровне ячейки растрового изображения на 9-41%. Также рассматривается предложение заменить значения космических изображений, в прямую зависящих от характеристик спектрального отражения лесных объектов, на географические матрицы лесных характеристик и использовать их при выделении площадей, сходных с таксационными выделами, определяемыми выделной лесной инвентаризации. Относительная эффективность сегментации, выражена уровнем уменьшения дисперсии основных таксационных показателей разделением лесного квартала на выдела, повысилась на 13-33%, когда в месте оригинальных космических изображений использовались непрерывные поверхности лесных характеристик.

**Ключевые слова:** лесная инвентаризация, космические изображения, лесные характеристики на уровне ячейки изображения, двух-фазовый отбор, к-ближний соседний, регрессия, сегментация.