Disturbance analyses of forest cover dynamics using remote sensing and GIS

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Abstract. Study of forest cover disturbance and its driving forces is one of the most significant areas in global environmental change research. Natural factors affecting forest disturbances are among the most significant drivers transforming the earth. Due to this reason remote sensing technologies take an important place in such research. Remote sensing and GIS techniques are widely used for forest cover monitoring under climate change and human impact but the lack of reliable information on forest use changes remains a major challenge of today. The purpose of this paper is a disturbance analysis of forest cover dynamics using remote sensing and GIS technologies. The research covers the changes in forest caused by different types of natural disturbance (forest fires, cutting, windfalls) and socio-economic factors (forestry reforms) in the Middle Volga region of the Russian Federation. This paper discusses the forest cover monitoring technique using satellite information and conducting assessments of forest cover disturbances that can be beneficial for the further research affecting changes over different time scales.

1. Introduction

Study of forest cover dynamics has become a central component in current issues for sustainable forest management and monitoring ecosystem changes[1-3]. Many projects [4, 5], such as Land-Cover / Land-Use Change (LCLUC), CORINE Land Cover Programme (Co-ordination of Information on the Environment) and Northern Eurasia Land Dynamics Analysis (NELDA), have been carried out by researchers around the world as case studies at different temporal and spatial scales.

Forest cover is a type of important form on the Earth’s surface due to its extensive use and change in time. The specificity of forestry is their dependence on climatic conditions and human activities that lead to the significant changes (forest health conditions, etc.). Therefore the assessment of risk from unfavorable phenomena, such as fires or drought, the consequences of social-economic reforms and etc., is important research topics. Due to the close connection between forest and consequences of socio-economic factors, investigations of forest cover change have been receiving particular attention [6]. The temporal and spatial change in forest cover has a significant impact on the ecosystem. Therefore, occurring processes and driving forces of forest change is of great significance for a regional research in the environmental policy and a decision-making in the sustainable forest management. Understanding the causes of different impact of driving forces on land cover and possibility to monitor changes is done in this study.

Satellite images play a key role in the study of forest cover changes. During the past decades the role of Remote Sensing (RS) and Geographic Information Systems (GIS) has increased significantly
In particular, the progress has been made in development of methods for extraction of thematic information from satellite images. This has resulted in improved opportunity for receiving up-to-date information about forest cover on the vast territories. The forest cover monitoring as well as the change detection is based on satellite images with different resolutions and time of an acquisition. Nowadays these issues are vitally important in the study of forest cover using RS and are an essential mutual theme for scientists all over the world as well. There are many methods for change detection with the use RS - from simple visual comparisons to detailed quantitative methods with providing the information about occurring changes, changes of the spatial objects, the types of land cover and accuracy assessment of results. This study is focus on one of methods.

The research object is a large part of the Republic of Mari El and Chuvashia which are located in the Middle Volga region of the Russian Federation. The region is of particular interest because it is representative of larger forest areas of in Europe and Western Russia that appears to be a large terrestrial carbon sink and an important general trend in land-cover change. The territory is hilly plain with an elevation range from 45 to 275 m above the sea level. The forest cover ranges between 16 to 57% across the region and the dominant species include pine (Pinus sylvestris L.), birch (Betula pendula Roth. and Betula pubescens Ehrh.), spruce (Picea abies Karst. and Picea obovata Ledeb.) and aspen (Populus tremula L.).

The background for the forest use changes in the region is the major social-economic reforms which changed the structure and forms of forestry management. The reforms include e.g. a new forest codex, lease relations in forestry, increase of export tax on timber wood. This has been leading to changes in forest management, illegal forest cuttings and, finally, to forest use changes on vast territories.

There is scanty information on actual state of forest cover and its changes (validation, examination). The major problems include the lack of complex assessment of changes in forest cover using RS data and of full analysis of influence social-economic factors across the entire region. Serious changes in forest cover occurred in the second part of XIX century. It was a time of intense forest exploitation and practices of timber harvesting. This has resulted to a significant reduction of spruce forests and increasing disturbances in managed forest ecosystems. Also, great forest fires of 1972 and 2010 of Mari El disturbed the most of coniferous forests that led to insect outbreaks on the burned areas. Nowadays a logging (both legal and illegal) is the major factor of forest changes in the Volga region.

The objective of this article is a disturbances analysis of forest cover dynamics using RS and GIS technologies. The focus is the use of retrospective analysis of satellite images from Landsat satellite in the Middle Volga region.

Created database for forest cover changes will be important indicator for solving issues in sustainable forest management in the future. Furthermore, it will be necessary for building forecasting models of the dynamics of ecological situation in the studied region. Analysis of forest disturbances during the last 30 years will provide a broad-scale evaluation of available forest cover, an assessment of human impact in particular on local scale and for international comparisons as well.

2. Materials and Methods

2.1. Research materials

A test site is a time series of at least 7 Landsat-resolution images (1985, 1988, 1999, 2001, 2010, 2011, and 2014) and Rapid Eye (2011) on the Volga region of Russia, which cover full Landsat scenes (180 x 180 km minimum). Several types of ground data used as reference data for forest cover mapping including forest inventory maps and database of forest surveys, plot measurements and transects.
2.2. Research methods

The Tasseled Cap transformation [13] for Landsat images has been used for the equation of different spectral signatures of vegetation changes during shooting images (Figure 1).

Figure 1. A time series of 1985-2014 Landsat images, with transformation Tasseled Cap.

This algorithm represents empirical equalization of spectral channels and linear transformation of bands to three indices: Brightness, Greenness, and Wetness. Brightness is associated with bare or partially covered lands, greenness - with green vegetation, and the last component, wetness, is associated with moisture, water and other moist features. Images after Tasseled Cap transformation (BGW) were used in the study of land cover for interpretation of objects.

For the data processing follow method were used:

- Thematic mapping of satellite images with accuracy assessment;
- Multifactorial and geo-statistical analyses of spatial data;
- Situational modelling of forest cover.

The research scheme is presented on the Figure 2.

Figure 2. The research scheme of method of disturbance analyses of forest cover dynamics.

Identification of the changes in forest cover associated with anthropogenic activities and natural phenomena is one of the important elements of the work in the classification of satellite images. The spectral characteristics of disturbed areas have similar indicators with other classes of land cover: grass or shrub vegetation. They are almost indistinguishable from Landsat satellite images. For such
tasks, spectral transformation or detailed mapping of satellite images is usually carried out in order to improve the accuracy of interpretation.

The algorithm for identification the changes in forest cover in the Middle Volga region was based on the methodology of a group of American scientists led by Professor Healy (2005). The proposed algorithm allows improving the interpretation of disturbed areas (cuttings, fires, forest stands drying, disease damage) by applying to the series of multispectral Landsat satellite images taken at the same time on the Disturbance Index (DI) calculated by the formula:

$$DI = B_r - (G_r + W_r)$$

where $B_r$, $G_r$ and $W_r$ are the components of brightness normalization of the transformed image Tasseled Cap “brightness”, “greenness” and “humidity”, respectively.

The combination of orthogonal coordinates “greenness” and “humidity” reflects the spectral characteristics of forest vegetation, and “brightness” more closely matches non-forest areas. Therefore, when calculating DI, the values of the brightness index in areas with recently disturbed forest cover are high, and the indices of greenery and humidity show lower values (Figure 3).

![Figure 3. Distribution index in the three-dimensional feature space Tasseled Cap. Pixels of disturbed areas are represented in red, non-disturbed ones - in blue.](image)

The DI is used for many tasks in the field of detecting changes in land cover. In this research, index is applied to a series of multispectral satellite images for evaluating a forest class mask (Figure 4).

![Figure 4. A series of multi-temporal satellite images Landsat with a Forest class mask used to determine DI.](image)
A comprehensive assessment of the disturbance of forest area includes the monitoring of forest fires, cuttings, dry stands and other violations during the studied period of time (1985-2014).

A detailed assessment of the disturbance is carried out within the limits of the studied one satellite image scene, which most fully covered the estimated forest areas affected by the forest fires (2010), cuttings, drying out of coniferous (spruce) plantations. The main part of forest land area fell on the northern part of the study scene.

The assessment of the extent of changes in the boundaries of disturbed plantations for the forest class is carried out on the basis of training samples (Region of Interest, ROI), taken from satellite images. For each estimated period, corresponding landfill sites of forest areas is selected, which were subjected to any violations as a result of a natural anomaly or anthropogenic activity. These polygons is used both for the subsequent supervised classification of satellite images and for assessing the accuracy of thematic mapping.

The spectral profiles obtained by combining a series of satellite images for different periods of time is used as the basis for interpretation disturbed areas. Figure 5 presents a graph of the DI values over time, showing changes in a forest area disturbed as a result of the 1988 clear cutting.

![Graph of the DI values curve for estimating disturbed areas](image)

**Figure 5.** Graph of the DI values curve for estimating disturbed areas (DI values curve on the disturbed area 1988).

To assess the areas covered by fire, data from multispectral satellite images of medium (Landsat) and high (Rapid Eye) resolutions was analyzed. Figure 6 shows the boundaries of fires in vector form, superimposed on the study area. The dynamics of changes in selected areas was also determined on the basis of the analysis and comparison of multi-temporal satellite images.

![Fragment of Landsat BGW images](image)

**Figure 6.** Fragment of Landsat BGW images: a) 2001, b) 2010 with fire boundaries.
As a result of the expert assessment of the Landsat satellite imagery series in the study area, 90 disturbed forest areas and 100 forest cover areas not affected by changes over the whole research period were identified.

The thematic map DI created in the software package ENVI-5.2 using the Maximum Likelihood method of supervised classification. This algorithm allows estimating unknown parameters by maximizing the likelihood function based on the generated training set. The classification is the overlay of the created polygonal data set of the training sample to the multispectral composite of a series of satellite images (1985, 1988, 1999, 2001, 2010, 2011, and 2014).

Assessment accuracy of the created thematic map was carried out by the method of post-classification data processing, including:

- Comparison with ground data (reference sites);
- Construction of a “matrix of inaccuracies” (Confusion Matrix);
- Calculation of the overall accuracy and Kappa coefficient.

A set of ground test data was carried out during field trips to forest sites and visual observation of the territory. Forest inventory, afforestation plans, high resolution satellite imagery and Internet-resources were used as additional materials.

Estimation of forest cover dynamics on the base of data of RS and GIS was done with the use of simulation models, which includes spatio-temporal changes in forest cover of the Middle Volga region. Spatial models based on the geographically weighted regression provide a better understanding of interaction between environmental factors and ecosystem processes under estimation of forest cover dynamics. The simulation model of forest cover dynamic includes different factors: cutting area, burned area, forest area and digital elevation model.

3. Results and Discussion

In this article, we used the integrated technique of RS and GIS to update data of the forest cover change for 1985-2014 in the Middle Volga regions and further examine the roles played by natural and anthropogenic factors in driving the change. The result of multiple unsupervised classification of satellite image Landsat data were thematic maps reflecting the spatial distribution of forest cover. Flora of studied region is includes the border of southern taiga and mixed forests (coniferous and deciduous).

Major changes in forest cover associated with timber harvesting, clear cutting, forest fires and drying of spruce stands are the result of drought 2010.

Mostly disturbed forest objects are represented by separate plots (cuttings that dry up tree stands) or large areas (burned in 2010). Significant areas of disturbances in the 1980s are more often the result of conducting intensive logging work.

Due to the increasing role of climate change forest fires become a main disaster. Also, during the dry season wetland (peat land, land with abundant moisture) are more dangerous from the point of view of forest fire. This is explained by the decrease areas of these classes during the research period.

According to the results of, it was established that the area of fire on the forest lands in the Republic of Mari El and Chuvashia within the limits of the studied scene reaches 79083.36 hectares. The forest fires of 2010 year seriously affected the forest lands of the Kilemarsky, Yurinsky, Kokshaysky, Kuyarsky, Morkinsky and Volzhsky forest districts of the Republic of Mari El, as well as the Ihresinsky, Cheboksarsky, Alatyrsky and Kirsky forestry of the Chuvashia Republic.

The article describes the approach of spatio-temporal analysis of forest cover dynamics. The methodology based on assessment of forest disturbance in time and space. Data analysis allows identifying changes in land use (when and where change is going on). The presented methodology will help to track the changes which taken place, to plan activities for forest planning, improve the forecasts of forest landscapes. In addition, the developed method will improve the efficiency of research work and activities of forest enterprises for estimation the changes of forest management and improve the quality of thematic mapping. Influence of social-economic aspects is also important in
these researches. Timely and accurate change detection is an important indicator in decision-making of sustainable forest management.

Forest cover changes and its border monitoring in time and space is a fundamental research [14, 15]. The results presented in this article can be used for the spatio-temporal analysis of forest cover with influence factors.

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