GIS-BASED FOREST COVER CLASSIFICATION AND MAPPING (PRINCIPLES AND TECHNIQUE)

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Abstract

Automated classification and mapping of forest cover can be accomplished only through interdisciplinary research efforts. A technique of automated classification and mapping of potential forest growing conditions and forest regeneration dynamics was developed and applied to south central Siberia. This technique is based on GIS-technology involving spatial analysis of a digital elevation model (Shuttle Radar Topography Mission (SRTM)), Landsat 5-TM images and ground observation data. In this way, an algorithm of conjugate analysis of dissimilar data *in a stepwise manner* was developed. *The vector maps obtained reflect forest growing condition types, forest types, and regeneration age stages. Although the obtained maps show current vegetation cover state, the map legend is based on the classification, which takes into account site-specific forest regeneration development. Therefore, these maps enable to predict forest regeneration dynamics in different growing condition.*

Keywords: *Central Siberia, digital elevation model (DEM), Geographical Information System (GIS), potential forest growing conditions, forest regeneration dynamics map, remote sensing data*

1. INTRODUCTION

Estimation and classification of vegetation cover spatial diversity is an important problem from scientific and practical points of view. Vegetation cover mapping is a very complex process; analysis of various kinds of information (ecological and geographical) is required for adequate representation of vegetation diversity on the map.

Continuously increasing anthropogenic impacts on the environment have resulted in a decrease of areas occupied by native undisturbed ecosystems. Vegetation cover is changed due to fires, logging, industrial activities and other influences. Many forest ecosystems have been disturbed and shifted from intact to successional state over the past 60 years. Monitoring of forest ecosystem diversity and sustainability under ever increasing human-caused environmental stresses is a major forest protection challenge.

Mapping is an important tool for studying and monitoring forest cover, particularly its spatial inventory, dynamics and biodiversity estimation. However, maps built using traditional methods become out of date very soon. Accurate vegetation cover maps created on the remote sensing data are missing for the most part of Siberia.

The present stage of thematic mapping is essentially based on using GIS-technologies and remote sensing data (Burnett & Blaschke 2003; Hill et al 2010; Wondie et al 2010; Ohmann et al 2011 & Higgins et al 2012). These methods allow to objectivize mapping process and to improve map accuracy and validity by automated processing of remote sensing data and field information in combination with traditional cartographic methods. Vegetation cover maps are actually spatial vegetation cover models, which reflect the diversity of vegetation and site conditions. Therefore, these maps can be used as a basis for spatial representation and modelling of different ecosystem parameters.

The purpose of our investigation is the development of an automated approach to classification and mapping of forest cover using GIS, remote sensing data, and ground observation data. To reach our purpose, we need to solve several key tasks in a stepwise manner. These tasks are as follows:

1. Inventory and classification of the current diversity and regeneration dynamics of forest cover.
2. Development of automated technique for classification and mapping of forest growing conditions.
3. Development of an algorithm for automated interpretation of Landsat-5 TM imagery.
4. Creation of a GIS-based map of forest cover current state taking into account forest regeneration dynamics.

2. MATERIALS AND METHODS

2.1. Study Area

The southern part of near-Yenisei Siberia was chosen to be a test site (56º - 58º N, 92º - 96º E). This area is heterogeneous topographically and consists of two distinct parts: West Siberian Plain west of and Central Siberian Plateau east of Yenisei including the low mountains of Yenisei Mountain Ridge and Usol Hollow. This fact is mostly a cause of natural vegetation cover diversity, which is essentially affected by anthropogenic factors.

A left bank part (relative to Yenisei River) of the study area is represented by sought taiga and subtaiga forests with patches of forest-step vegetation and agricultural lands. Right bank study area is characterized by mountains taiga forests in the range of Yenisei Mountain Ridge. Forest-step vegetation surrounded by subtaiga forests is situated eastwards.

Forest vegetation changes considerably depending on site conditions. Elevated watersheds are covered by mixed stands of Siberian pine, spruce, and fir. Understory vegetation is represented by taiga forbs, small shrubs, and mosses. Podzolic soils are common under dark conifer stands (Gorbachev 1967; 1992).

Spruce forest covers small river valleys. Scots pine stands are widely spread in lower watersheds, mixed Scots pine/larch stands occupying watershed slopes. Podzolic and sod-podzolic grey forest soils with a second humus horizon occur under Scots pine/grass stands.

Mixed fir/Siberian pine/spruce forests prevail in the Yenisey Mountain Range (Lapshina et al 1971). These dark conifer taiga forests are characterized by polydominant stand canopies contributed mainly by fir, with spruce and Siberian pine (somewhere Scots pine and larch) being permanently present. Deciduous species proportions vary greatly (from 10-20 to 100% of a stand), which is related to post-fire and post-logging forest regeneration periods, as well as to aging-caused stand changes. There are 6-7 dominant species, whose contributions to stand canopy vary with forest growing conditions. Therefore, the forests of the area are markedly diverse in composition, structure and regeneration dynamics of vegetation communities comprising them. They are heavily disturbed by both natural and human factors. Big areas are covered by age stages of native forest regeneration in a range of forest growing conditions. In this respect, a development of appropriate classification of forest cover diversity taking into account characteristics of forest regeneration dynamics in various growing conditions is considered as a research priority.

2.2. Principles and Methods

The development of appropriate vegetation classification, upon which the map legend would be based, is a key task for thematic mapping. In this work, a classification of forest cover was performed using principles and an approach of Russian forest scientist Kolesnikov (1956). According to this approach, forest ecosystem diversity is formed by forest development or regeneration stages present at the same time in a given area. The entire diversity of vegetation communities is classified based on growing condition similarity, and not based on continuously changing outward characteristics (e.g., species composition). The approach to classification of forest vegetation is based on a concept that all stands found within an area relatively uniform in geographic location and topography are of a common origin, i.e. they are considered as the age stages of the major-woody-species stand for certain forest

growing conditions. Secondary and major woody stands (stand types) occurring in a certain type of forest growing conditions are grouped to make a major forest regeneration series. This series is called forest type.

Therefore, forest type as a main unit of this classification represents a series of sequentially replaced communities developing within a certain type of forest growing conditions. Growing conditions type presents a key element of the forest type concept. It is identified on the basis of climate, geological, geomorphological, and soil parameters of a given area.

This approach opens new possibilities for mapping vegetation cover dynamics using GIS. With this approach, diversity of forest communities is classified based on similarity of forest growing conditions. Sites similar in topographic location, combination of relief elements, and, hence, in ecological regimes controlling vegetation are identified in the area of interest based of DEM analysis.

GIS "Forests of Central Siberia" (Cherkashin and Korets 2004) and subsystem "Forest Dynamics and Diversity" (Ryzhkova et al 2004) were used to develop an algorithm of automated mapping of forest regeneration dynamics. The GIS basic information layers, such as a topographic base map, a raster-vector relief model, satellite imagery, general geographic and thematic maps, and a database of ground observations on sample sites were used and their spatial analysis was carried out.

Satellite data processing involved several stages. The first stage was preliminary data processing that included image geometrical correction and transformation to desirable map projections, georeference, as well as radiometric correction and preliminary processing of multiband images to increase their quality. At the second stage, normalized images were used to carry out thematic processing of remote sensing data. This was done by pattern classification and recognition methods. The third stage of remote sensing information processing involved the resulting data expert estimation.

To carry out automatized classification of a DEM-composite (elevation above sea level (a.s.l.), slope) and satellite images, we used standard methodologies, such as ISODATA and MAXLIKE (Richards & Xiuping 2005) as well as ERDAS IMAGINE 9.2 product.

3. RESULTS

A technique of automated classification and mapping of forest growing conditions and forest regeneration dynamics was developed and applied to south central Siberia. This technique is based on GIS-technology involving spatial analysis of multi-band satellite data, digital elevation model (DEM) and ground observation data.

Automated mapping of forest cover, particularly its regeneration dynamics, is a challenging problem covering a number of tasks, which can be accomplished only through interdisciplinary research efforts. In this work, an algorithm of conjugate analysis of dissimilar data was developed to solve several key tasks in a stepwise manner.

3.1. Inventory and preliminary classification of the current diversity and regeneration dynamics of test area forest cover

The first task is to develop an appropriate vegetation classification, upon which the map legend would be based. Using the above principles, a preliminary inventory of the potential forest growing conditions and the associated vegetation types was developed for the study area typical of plain and low-mountain southern taiga forests found along Yenisei River. We used Digital Elevation Model (SRTM-3-DEM) (http://www2.jpl.nasa.gov/srtm/russia.htm) to build topological transects that crossed the study area and analyzed these transects using the thematic and general geographic maps contained in the GIS database, literature information, and ground observation data.

Using these profiles and landscape maps (Sochava 1977; Gudilin 1987), we analyzed geomorphological conditions of the area of interest and identified sites relatively similar in relief characteristics (i.e., in mesorelief form, range of elevations above sea level, and dissection of surface).

One of this transects is shown in Figure 1. The seven identified classes represent certain landscape types and their combinations and presumably correspond to different geomorphological complexes (GMC) of forest growing conditions. Therefore, preliminary number of classes for an automated DEM classification was determined.

Woody species composition of dominant native and secondary forest types were determined for each class for further more detailed classification of current forest cover.

Forest regeneration series typical for different forest growing conditions were identified for the plain and low-mountain GMCs of the test area using ground, archive, and literature data. A preliminary conjugated classification of forest types with an account of forest growing conditions was developed.

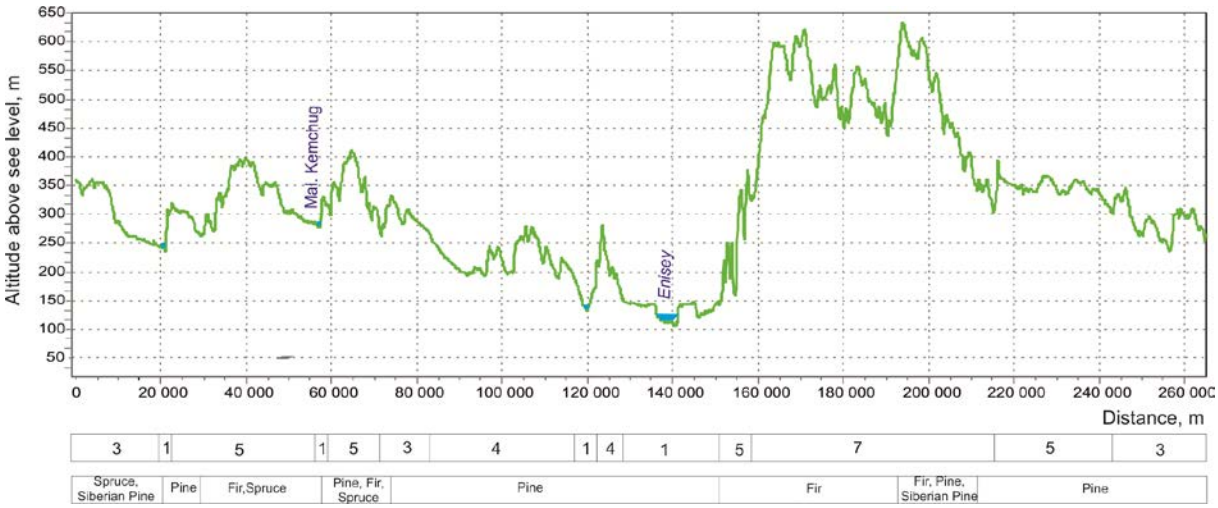

Fig.1. DEM-based topographic profile for preliminary inventory of the potential forest growing conditions and the associated vegetation types; Land cover classes 1-7 presumably correspond to geomorphological complexes (GMC) of forest growing conditions and are relatively similar in certain ranges of relief morphometric parameters (see characteristics in Table 1)

The brief description of the main forest types identified in the study area is given below.

Scots pine-dominated types

1. Scots pine/ tall grass/forb stands supported by dark-colored sod forest soils and dark-grey loamy forest soils occur in watersheds and on the adjacent very soft slopes; site classes II and I.

2. Scots pine/forb stands on sod-slightly podzolic, sod acidic forest, and grey loamy forest soils limited to soft slopes; site classes II and III.

3. Scots pine/forb/whortleberry (*Vaccinium vitis-idaea*) stands on sod-podzolic soils and light-grey forest loamy sand on moderately steep slopes; site classes II and III.

4. Scots pine/ feather moss/forb stands on coarsely humic podbur on steep slopes lining Yenisei river and its tributaries; site class III.

5. Mixed Scots pine/dark conifer/tall grass stands supported by dark-grey forest soils and sod-humic-gley soils in saddles between softly sloping elevations and flat bottoms of small valleys; site classes I and II.

6. Mixed Scots pine/dark conifer/feather moss/grass stands on lightly loamy podzolic soils in convex watersheds in the lower part of the Yenisei Mountain Range; site classes II and III.

7. Scots pine stands supported by grey forest and sod-podzolic soils on steppe sites; site class III.

Mixed fir/spruce types

8. Fir/spruce/tall grass/forb stands supported by dark-colored sod forest, dark-grey, and double-humus-horizon moderately loamy sod-podzolic soils on flat-topped elevations and the adjacent soft slopes of an accumulative high plain; site classes II and III.

9. Mixed fir/spruce/grass stands on sod-podzolic and grey forest soils on an accumulative high plain slopes; site class II and III.

10. Mixed fir/spruce/tall grass stands with a minor component of Siberian pine on sod-humic-gley and humic-peat soils in flat-concave valley bottons; site classes II and III.

11. Mixed fir/spruce/feather moss/short grass stands on sod-podzolic loamy soils on flat watersheds and soft slopes in the low-elevated part of the mountain range; site classes II and III.

12. Mixed fir/spruce/feather moss/forb stands on sod-podzolic loamy soils on various slopes in the low-elevation part of the mountain range; site classes II and III.

Mixed fir/Siberian pine/spruce types

13. Mixed fir/Siberian pine/spruce/feather moss/sedge stands on sod-heavily podzolic loamy soils and coarsely-humus podbur on moderately steepslopes of the eastern macroslope; site class III.

14. Siberian pine/fir/spruce/feather moss stands on gley-podzolic soils in flat parts of hollows and shallow valleys; site classes III and IV.

15. Mixed fir/Siberian pine/feather moss/sedge stands on podzolic soils with crushed stone and coarsely-humus podbur on convex watersheds and steep slopes along the mountain range axis; site class III and IV.

16. Mixed fir/Siberian pine/spruce/feather moss/short grass stands on sod moderately-to-heavily podzolic soils on flat-convex watersheds along the axis (i.e., the highest part) of the mountain range; site classes III and II.

17. Mixed fir/Siberian pine/spruce/feather moss/forb stands on sod-podzolic soils on moderately steep slopes in the highest part of the mountain range; site classes II and III.

Mixed spruce/fir types

18. Mixed spruce/fir/grass/bog stands on alluvial-bog and peat soils in river flood-plains; site classes IV and V.

19. Mixed spruce/Siberian pine/fir/feather moss/horsetail stands on alluvial sod acidic soils in high river plains; site classes III and IV.

Mixed Scots pine/larch types

20. Mixed Scots pine/larch/forb/whortleberry/feather moss (*Vaccinium vitis-idaea*) stands on sod-podzolic and podzolic soils of light texture on soft slopes of river terraces; site class III.

Scots pine waterlogged types

21. Mixed Scots pine/spruce/Siberian pine/birch/forb/sedge/sphagnum waterlogged stands on alluvial moor peat soils in river flood valleys and on low river terraces.

Therefore, a preliminary classification of forest growing conditions taking into account site topology and the associated forest types was developed for the study area.

3.2. Development of automated technique for classification and mapping of forest growing conditions

The next step is an automated classification and mapping of potential forest growing conditions. A preliminary number of classes for an unsupervised DEM classification was determined at the first step. To establish the boundaries of these classes, a two-layer (elevation and slope) image was classified

using ISODATA (Richards & Xiuping 2005). This enabled to identify seven land cover classes relatively similar in morphometric relief parameters.

Climate is an important part of forest growing conditions. Thus, the classification of spatial distribution of climatic parameters was carried out for the study area. Similarity of climatic conditions was estimated with help of empiric models of spatial distributions of such parameters as average July mean temperature over many years and average annual precipitation. These models are described in the earlier works (Onuchin, 2002; Onuchin & Danilova 2012). Using ISODATA (Richards & Xiuping 2005) an unsupervised classification of two-layer image (average July mean temperature over many years and average annual precipitation) was carried out, and five land cover classes similar in climatic parameters were obtained. They correspond to fragments of climatic zones and subzones (Danilova et al 2013).

For analysis and classification of dissimilar data (morphometric and climatic parameters), expert system (decision tree) was created using Knowledge Engineer module / ERDAS Imagine in order to build geomorphological complexes of forest growing conditions. Input variables of the decision tree are the raster layers of spatial distribution of environmental factors (morphometric and climatic parameters).

Using morphometric and climate parameters layers, expert classification was carried out and nine (I-IX) classes relatively similar in morphometric and climate parameters were obtained. These classes were interpreted as a GMK of potential forest growing conditions with respect to geomorphology, zonal soil types, and vegetation. A map of potential forest growing conditions on the level of geomorphological complexes of forest growing conditions (the highest-rank classification unit) was build for the study area (Fig. 2).

More detailed units, forest growing conditions (FGC) types, were identified for each geomorphological complex (GMC) based on the ranges of slope and elevation above sea level (a.s.l.). For refining the classification, we identified sites that were relatively homogeneous in slope (flat surfaces (0-1°), soft slopes (1-3°), moderate slopes (3-5°), steep slopes (5-8°), very steep slopes (8-15°), benches and rocks (>15°)), which have relatively similar soil conditions and hydrological regimes and correspond to FGC types.

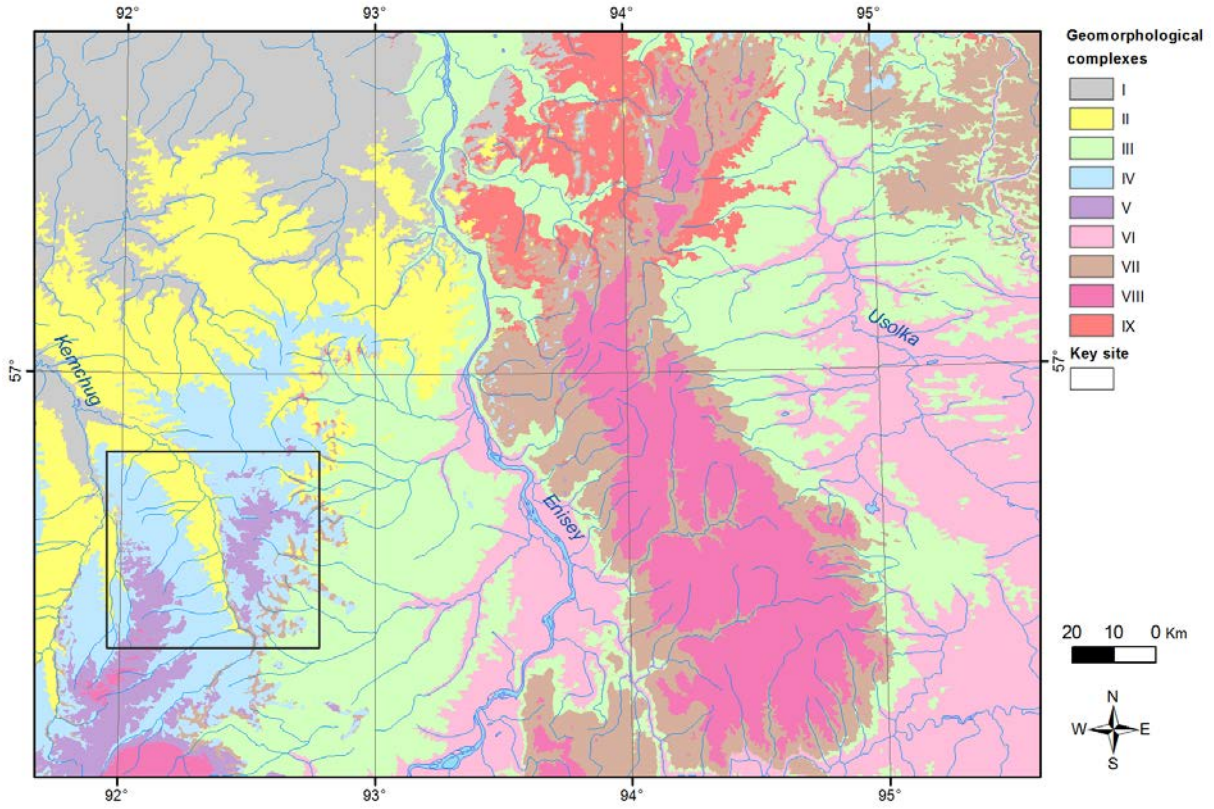

Fig. 2. Map of potential forest growing conditions for the study area (layer of geomorphological complexes of forest growing conditions).

As a result, raster layers of surface dissection elementary classes and landcover classes were obtained. An expert identified the elementary land cover classes resulting from the DEM-composite image analysis as flat interfluves, slopes of different steepness, river valleys, and floodplains found within each GMC of growing conditions. These classes constituted the next level of growing conditions map, which is required for correct identification of age stages and regeneration series built from them. A map fragment of FGC types layer corresponding to more detailed hierarchical classification level is presented in Figure 3. The map shows sites similar in topographic location, soil, and hydrological conditions, i.e. in ecological regimes, which determine the variety of vegetation cover. This map provides the basis of forest regeneration dynamics mapping.

3.3. Development of an algorithm of automated interpretation of Landsat-5 TM imagery

The next step was an automated classification of multi-band satellite images. We have developed an algorithm of automated recognition of forest regeneration stages based on a spatial analysis of remote sensing and ground data (Danilova et al 2013).

Landsat 5-TM images were classified by the method of maximum likelihood to identify land cover classes based on spectral characteristics. We used four summer (June-July) and four autumn (September-October) cloud free Landsat 5-TM scenes (1989-1990 years) received as close as possible to the periods of field studies and ground forest inventory. To classify multitemporal images, the training samples for major woody species and age were prepared. The information classes were formed through the elementary forest inventory site database query. As a result, the information classes most common in a given part of the test site and the associated image were developed. Then parametric signatures were calculated for each information class and a supervised classification of the images was done based upon these signatures. A generalized raster layer of surface spectrum-based elementary land cover classes was obtained using a fuzzy composition approach (ERDAS 1999).

Accuracy assessment of image classification was performed using Kappa statistic. Kappa coefficient is equal to 0.74, therefore the satellite imagery classification quality corresponds to the excellent object recognition accuracy (Monserud & Leemans 1992).

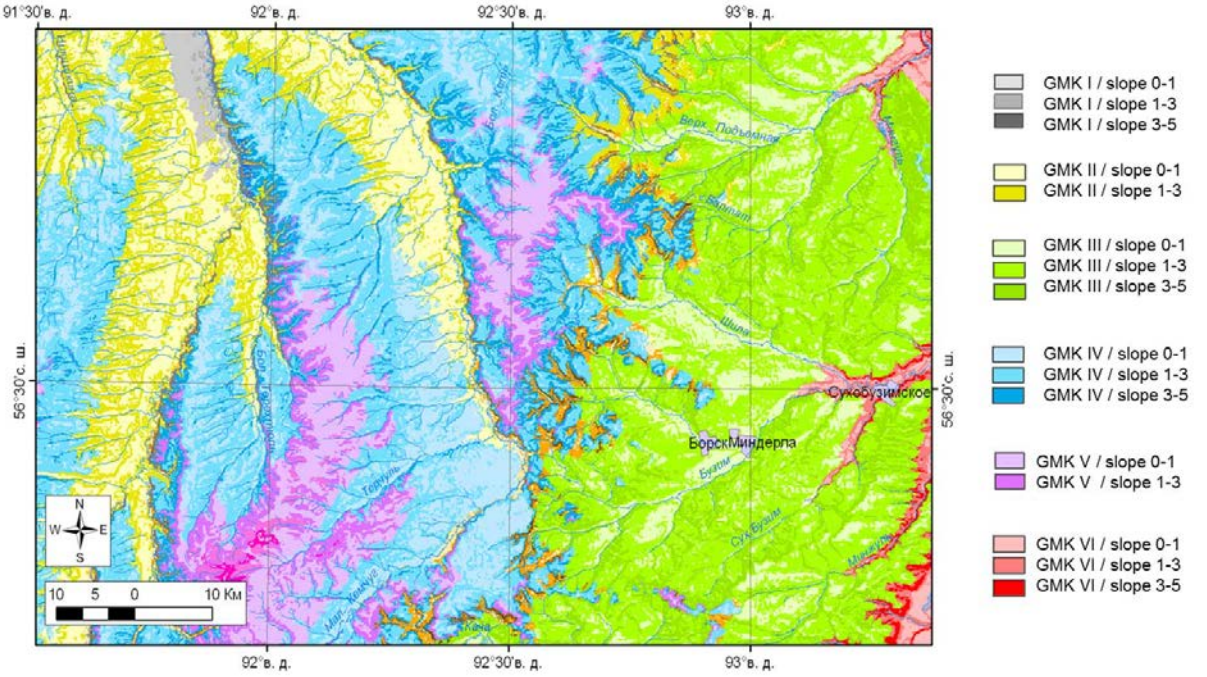

Fig. 3. Fragment of a map of potential forest growing conditions (key site on fig. 2); layer of forest growing conditions types.

Therefore, 50 classes of land cover were obtained and 20 of them were interpreted as forest cover classes. These classes were then visually assigned to the different forest regeneration stages by expert judgment with the help of available reference data.

3.4. Development of a GIS-based map of forest regeneration dynamics

Finally, the obtained classes were interpreted by an expert as forest regeneration stages or age stages with the help of forest inventory data. There are forest regeneration stages of different age: initial regeneration stages (burned and logged sites); young (up to 40 years old) deciduous stands; deciduous stands aging 40-80; conifer stands 80-120 years old approaching cutting age; and mature and old conifer stand over 120 years of age.

To correctly classify and understand the position of any stage in a forest regeneration series and to assess its current state, one needs to analyze the forest growing conditions controlling the probability of occurrence of any forest type (regeneration series). The elementary land cover classes obtained from remote sensing data classification were distributed among regeneration series using a preliminary classification of growing conditions types and the associated forest vegetation (Ryzhkova, Danilova & Korets 2011).

To build a forest regeneration series layer, an expert classification based on the Knowledge Engineering Module (ERDAS 1999) was developed. The results of the analyses of the satellite images

and forest growing conditions raster layer were used as the input data for building the expert classification.

As a result, raster and vector polygonal layers were built. They are the maps reflecting the distribution of vegetation regeneration series (forest types) (fig. 4) and regeneration stages (fig. 5) in a range of forest growing conditions. A fragment of conjugate classification of forest growing conditions and forest vegetation is presented in Table 1. It is the base of map legend. It summarizes the characteristics of geomorphological complexes of forest growing conditions (with an account of geomorphology and zonal soil), growing conditions types, forest types, and forest regeneration stages.

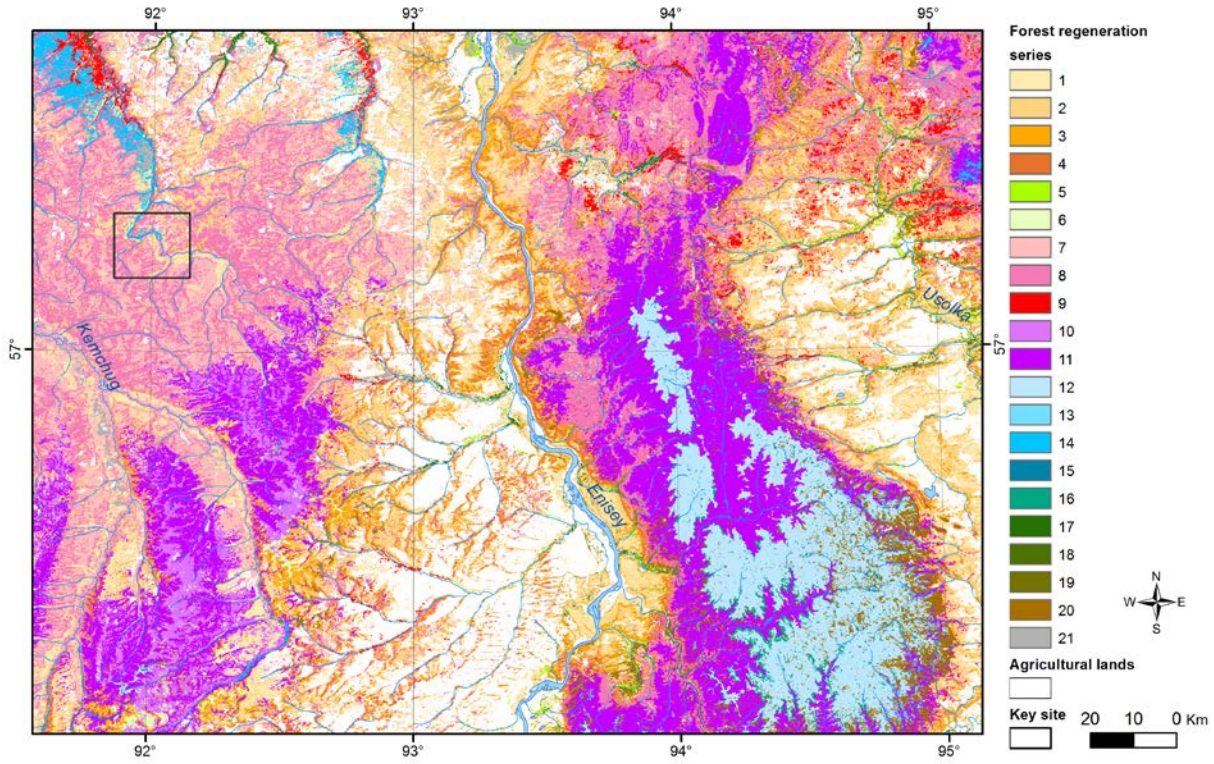

Fig. 4. Forest regeneration dynamic map of the study area (layer of regeneration series). See the description of regeneration series in the text.

The forest regeneration dynamics map developed through application of ground and satellite data for the southern part of Yenisei Siberia within Krasnoyarsk Region is of a scale of 1: 200 000. On the one hand, this map reflects the current state of forest cover. On the other hand, it shows spatial distribution of forest regeneration series in a range of growing conditions since it is based on the dynamic classification.

Therefore, this map enables to assess current state of forest vegetation, and to predict vegetation succession directions and rates in different growing conditions.

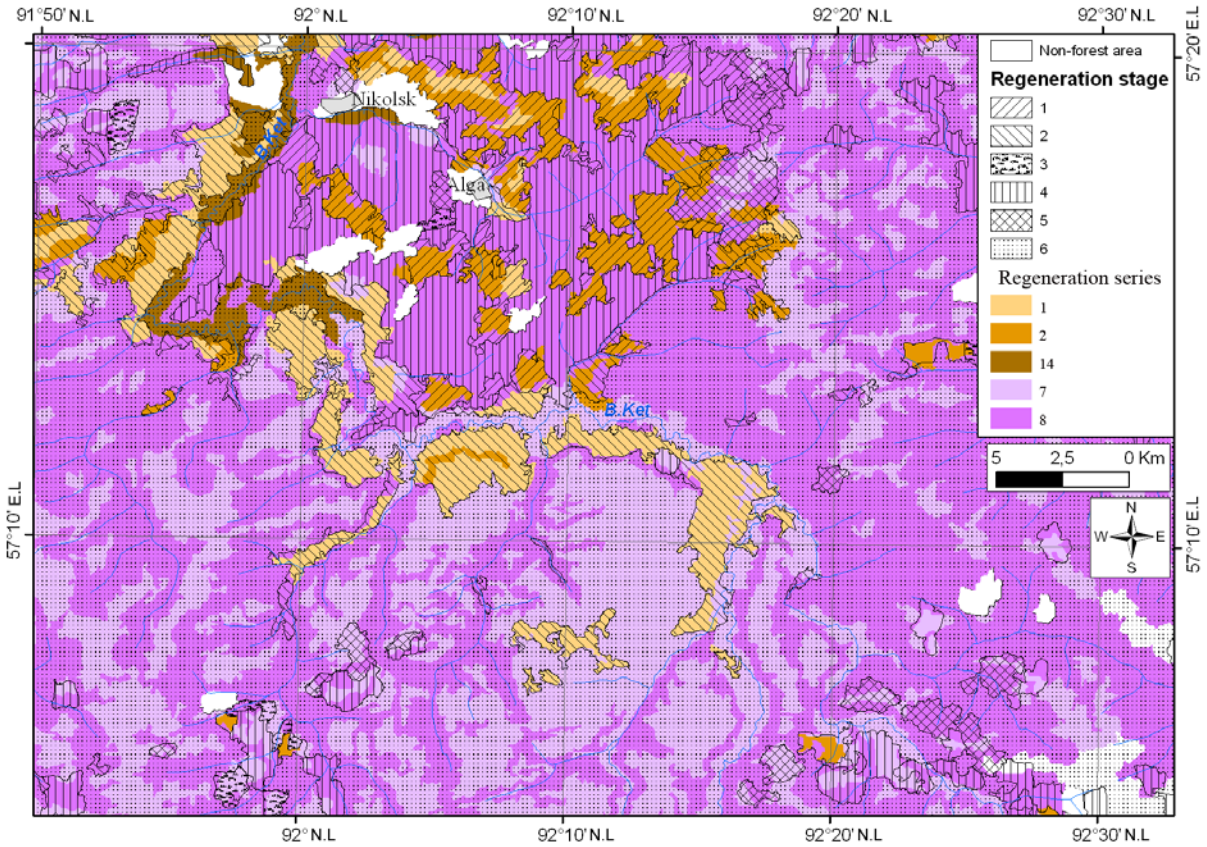

Fig. 5. Fragment of two-layer forest regeneration dynamic map (key site on fig.4). See the description of regeneration series and stages in the text.

Table 1. Forest growing conditions and the corresponding forest types (forest vegetation regeneration series)

Forest growing conditions			Predominant vegetation	
Geomorphological complex of forest growing conditions (GMC)		Type of forest growing conditions (based on slope range)	Forest types number (discription in the text)	Secondary vegetation
II. Elevation above sea level, m: 224-288 Slope, deg.: 1,3 ± 0,8	Elongate-elevated or rolling, elevated and flat denudation, and denudation-erosional plains made up by eluvial-deluvial and alluvial-deluvial brown heavy loams, brown loessed clays and loamy sands on river terraces. The soils are dark-colored sod-meadow, sod-gley, forest grey and double-humus-horizon dark-grey and sod-podzol.	0-1 1-3	1, 8 2, 3, 9	1) grass canopy (initial forest regeneration stage); 2) young (up to 40 years old) deciduous stands; 3) young and middle-aged (40-80) birch and aspen tall grass/forb stands; 4) mixed conifer/deciduous stands (80-100); 5) ripening conifer stands; (80-120); 6) mature and old conifer stands
III. Elevation above sea level, m: 118-262 Slope, deg.: 2,3 ± 2,2	Elongate-elevated or rolling, elevated and ridged (riverside), denudation, and denudation-erosional plains made up by light-brown and yellow-brown loessed deluvial-eluvial mid-weight and light pulverescent- limous clays, and, on high-to-middle river terraces, by light loams and loamy sands. The soils are of the dark-gray and grey forest type, leached chrnozems, in places, grass sod-podzilic and podzolic.	0-1 1-3 3-5 5-8	1, 8, 10 2, 9 3, 9 4, 9	
IV. Elevation above sea level, m: 275-363 Slope, deg.: 1,8 ± 1,3	Hilly-ridged or rolling soft sloping, low slightly dissected plateau made up by eluvial-deluvial and alluvial-deluvial brown heavy loams The soils are grass sod-podzolis (grass sod-deep podzolic), forest grey.	0-1 1-3 3-5	1, 2, 11 12 13	
V. Elevation above sea level, m: 332-432 Slope, deg.: 3,4 ± 2,2	Hilly-ridged, ridged-bold-hilled dissected plateaus with different slopes made up by proluvial and eluvial-deluvial brown and red-brown, crush-stoned, heavy loams and loamy sands. The soils are grass sod-podzolis (grass sod-deep podzolic), forest grey, gleic.	0-1 1-3 3-5 >5	6, 11 3, 11, 12 3, 12 3, 4, 12	

4. CONCLUSIONS

An algorithm for conjugate analysis of dissimilar data in a stepwise manner for spatial modeling of potential forest growing conditions and forest regeneration dynamics was developed using standard software (ArcGIS, ERDAS). This algorithm involves spatial analysis of multi-band satellite data, a digital elevation model, and ground measurements. Based on this algorithm, vector maps reflecting the diversity of forest growing conditions and forest regeneration series and stages were developed to south central Siberia.

The combined use of automated methods and expert interpretation of the obtained classes allow us to carry out an automated classification and mapping of forest cover characteristics, directly invisible in space images, but very important regarding thematic mapping (forest growing conditions types, forest types, age stages of forest regeneration). The great advantage of the proposed approach is a possibility of revision and updating the obtained map models in case of vegetation cover changing and maintenance of data.

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