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GIS-AIDED METHOD OF FOREST CURRENT STATE AND DYNAMICS MAPPING

KORETS M., RYZHKOVA V., DANILOVA I.
Sukachev Institute of Forest SB RAS, KRASNOYARSK, RUSSIAN FEDERATION

ABSTRACT

This paper addresses a GIS-aided method of forest vegetation dynamics mapping based on a combined analysis of multi-band optical satellite data, a digital elevation model, and ground data. An unsupervised classification procedure applied to remote sensing scenes and digital elevation model composite (elevation, slope and curvature) images was used to map forest vegetation dynamics and growth conditions in combination with spatial intersection and generalization approaches. Based on the methodology described below, Landsat 7 ETM+ satellite imagery, SRTM 90m digital elevation model, and field data were processed for the Lower Angara test site. The resulting map included a polygonal vector layer of forest regeneration stages and a layer of forest vegetation succession series in a range of site conditions.

KEYWORDS

GIS, digital elevation model, remote sensing data, stand type, site conditions, forest regeneration dynamics map.

INTRODUCTION

Forest conservation and assessment of the current vegetation condition are among the highest priorities of sustainable forest management under ever increasing human environmental impact. Siberian boreal forests have been drastically changed by logging, fire, insect outbreaks, industrial pollution, and other disastrous events over the past 50 years. As a result, the natural forest ecosystem balance has been much disturbed, including changes of forest functions and biodiversity.

Mapping is a major tool of studying vegetation cover, as it enables spatial inventory of vegetation cover, estimation of its dynamics and diversity. Estimating current state and regeneration dynamics of forest ecosystems is crucially important today in the context of ever-growing human influence on the environment. Forest cover mapping is a basic component of forest monitoring systems that provides spatial aspects of estimation of current changes of forest state and dynamics caused by different factors.

Maps built using traditional methods become out of date very soon. At present, building new or updating old maps involves use of satellite images and GIS technologies in combination with traditional mapping methodologies. A major weakness of traditional map building is that objects of interest are delineated based on visual interpretation (Konovalova et al. 2005; Mkrtchan 2006). With GIS technologies, visual interpretation-based judgment is reduced to minimum, since using these technologies enables development of methods to identify land cover units having similar pre-set characteristics that can be based upon for detailed division of land covers, such as forest cover.

This study attempted to approach forest inventory, mapping, and estimation of the current vegetation condition and regeneration dynamics using GIS technologies. This information could be used in developing a human-caused forest disturbance monitoring system.

Increasing aerial and satellite information used in building and updating GIS-based thematic maps, as well as a growing need for its high accuracy and rate of interpretation necessitate automation of satellite data processing and thematic mapping procedures.

Approaches to GIS-based mapping of hierarchical ranks of vegetation-topography complexes using robust information processing algorithms are discussed in a number of papers published over the past several years (Konovalova et al. 2005; Sysuev 2006; Yermakov et al. 2007). These algorithms cover baseline field data collection and processing, remote sensing data interpretation, and automated development of thematic maps. The resulting land cover units differ in thematic characteristics, size, and hierarchical rank.

The arch focus of most studies addressing thematic map development based on digital elevation models (DEM) is landscape mapping. Landscape units are identified using automated classification of DEM (Mkrtchan 2006) and satellite imagery (Puzachenko et al. 2003; Konovalova et al. 2005) or by their spatial analysis (Merekalova 2006). Noteworthy is a method of determination of potential type of topography-controlled vegetation growing conditions based on detailed analysis of DEM morphometric characteristics proposed by Sysuev and Shary (2000).

Our study focused on developing an algorithm of computer mapping of forest ecosystem regeneration dynamics using GIS technologies.

Computer programs available nowadays to process remote sensing data (RSD), as well as increasing space imagery resolution allowed to automate traditional methods of RSD analysis to a fairly high level and to combine them to constitute a single technology. Use of this technology facilitates RSD analysis and provides higher reliability and detail of its results (Konovalova et al. 2005).

TEST SITE CHARACTERISTICS

This study was conducted for Angara region, the southernmost geographical province of the central Siberian geographical area found within the Central Siberian Plateau. This test site is an elevated plain gently sloping northeastward and having both plain and mountain topographical characteristics. Angara folds and multiple trapp outcrops occur in this generally plain area. The surface structure non-uniformity accounts for diverse forest vegetation in this area. The test site is within the southern taiga and subtaiga forest district of the Angara-Tunguska forest province. According to more detailed vegetation zoning conducted by Popov (1982) for the southern taiga forest subzone of central Siberia, parts of the test site occur in four forest districts of the Chuna-Angara subprovince of the Angara southern taiga forest province. The test site is located on the Angara trapp plateau elevated 300-500m above sea level (a.s.l.).

The site is in extremely continental climate, climate continentality increasing west eastward. Average annual air temperature is -2.1 to -2.4 C, average monthly temperature fluctuating between 40°C and 43°C. Annual precipitation is 320-490mm and decreases northeast southwestward. Winter precipitation (100-160mm) accounting for 25-35% of the total annual precipitation received by this area is sufficient to form 35-70cm deep snowpack (Popov 1982). Permafrost occurs as “islands” and covers 20-30% of the total area.

Forest vegetation characteristics change considerably with elevation, particularly in the mountain-like parts of the test site. However, elevation-caused vegetation changes are also observed in the elevated plain parts. Altitudinal subbelts of light (the lower subbelt) and a dark (the upper subbelt) conifer forest are found across the site (Popov 1982). Elevated watersheds (over 600m a.s.l.) located on the Angara folds are covered by Siberian pine stands, whereas dark conifers occur as low as 400m a.s.l. Scots pine stands are widely spread in lower water, mixed Scots pine/larch stands occupying watershed slopes. Spruce forest covers small river valleys. Secondary birch stands accounting for 10-15% of the total forest area are initial post-fire or post-harvesting stages of Scots pine, larch, and spruce forest regeneration (Popov 1982).

Analyzing genesis of and classifying Angara forests is a complicated task, as these forests are heavily disturbed by fire and are, hence, represented by different post-fire vegetation regeneration stages.

MATERIALS AND METHODS

We developed a methodology of automated mapping of forest regeneration dynamics using “Forest Dynamics and Diversity” subsystem of GIS called “Forests of Central Siberia” (Cherkashin and Korets 2004). The GIS basic information layers, such as a topographic base map, a raster-vector relief model, aerial and satellite imagery, general geographic and thematic maps, and a database of ground observations conducted on sample sites, were based upon to develop the GIS subsystem.

Aerial and 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 RSD processing. This was done by pattern classification and recognition methods. These methods helped find a decision rule, which allowed us to divide multidimensional attribute space into areas related to each class of objects. This division was done so that a certain class of objects could be unambiguously assigned to any image pixel described by a certain vector in the attribute space. Classification is usually based on statistical pattern recognition methods that use probability distribution functions to which pattern classes are assigned. There exist two most widely used classifications: unsupervised and supervised classifications (Richards 2005). The unsupervised classification is based on cluster analysis and image pixels are divided into classes without use of a priori knowledge of existence and names of these classes. In this case, number of classes is found based on number of peaks in brightness histograms. Where a priori empirical data constituting a training sample are available, the supervised classification is used.

The third stage of remote sensing information processing involves expert visual interpretation of the resulting data. The data can be estimated qualitatively (comparative estimation) or they can be quantified, when values are obtained indicating the resulting raster map accuracy range.

We thematically classified two image types: a multiband and a multichannel image. The latter was an image of relief characteristics (DEM composite) including layers of elevation above sea level, slope, and surface curvature. These image types can be thematically processed separately using standard procedures of supervised or unsupervised classification. These procedures can also be used in succession, with an interim stage of identification and correction of an information class set. ISODATA procedure (Tou and Gonzalez 1974) is often used as a method of unsupervised classification, whereas algorithms of parallelepiped, minimal distance (MINDIST), and maximum likelihood (MAXLIKE) (Richards 2005) are widely applied to carry out supervised classification. Today's software packages also contain more sophisticated algorithms of image segmentation using contextual spatial information, for example, texture and form.

To develop an automated mapping methodology, we used the most widespread thematic classification procedures (ISODATA and MAXLIKE) that proved to be effective. These procedures are included into all available image processing software packages, such as ERDAS Imagine, ENVI, SCANEX Image Processor, and ArcGIS Image Analyst.

Automated mapping of vegetation cover, particularly its regeneration dynamics, is a challenging problem covering a number of tasks which can be accomplished only through interdisciplinary research efforts.

The regional vegetation was classified using Kolesnikov's (Kolesnikov 1956) topogenetic approach, which classifies forest vegetation communities by community genesis, development trends, and similarity of site conditions (or forest environments), rather than by constantly changing external parameters, such as species composition.

The major unit of Kolesnokov's (1956) topogenetic forest cover classification is forest type, which is interpreted as a series of genetically linked successive vegetation communities developing under forest site conditions of a certain type. Type of forest site conditions is identified based on geological and geomorphological structure of any given area. This topogenetic approach to classification of forest vegetation is based on a concept that all secondary stands found within an area relatively uniform in geographic location and topography are of a common origin (or genesis), i.e. they are considered as the age stages of the major-woody-species stand characteristic of certain forest vegetation site conditions. Secondary and major woody stands occurring in a certain type of forest site conditions are grouped to make a major vegetation regeneration series. This series is called forest type.

To develop a classification of vegetation and corresponding growing conditions, the test site was analyzed using the thematic and general geographic maps contained in the GIS database, literature information, and ground observation data. DEM-based coarse-scale topographic profiles showing geomorphological characteristics of the site were built. Using these profiles and landscape maps (Landscapes of Southeastern Siberia 1977; The USSR Landscape Map 1987), we analyzed geomorphological conditions of the test site and identified sites fairly similar in relief (i.e., in mesorelief form, range of elevations above sea level, and terrain roughness) that assumingly correspond to different geomorphological complexes (GMC) of forest vegetation growing conditions. Woody species composition of dominant major and secondary forest types was determined for each GMC.

This approach is considered to be particularly promising for the forests of Angara region, since they are heavily disturbed by fire and logging and are largely represented by different vegetation regeneration stages.

RESULTS AND DISCUSSION

A methodology for building a forest regeneration map based on spatial analysis of Landsat ETM+ imagery, a digital elevation model (DEM), and ground data was developed and tested for a test site in Angara region using "Forests of Central Siberia" GIS (Cherkashin, Korets 2004).

The map building included the following steps (Fig. 1):

1) preparation of input data (satellite images and DEM);

2) calculation of additional DEM features (development of a DEM composite);

3) unsupervised classification of remotely sensed and DEM-composite images;

4) analysis and identification of the initial information classes;

5) selective generalization and elaboration of the information classes;

6) development of forest vegetation and growing conditions (or forest environment) raster maps;

7) conversion of the raster maps into vector maps followed by spatial intersection and generalization of the latter; and

8) analysis of the combinations of the spatially intersected classes and development of vegetation regeneration map classes.

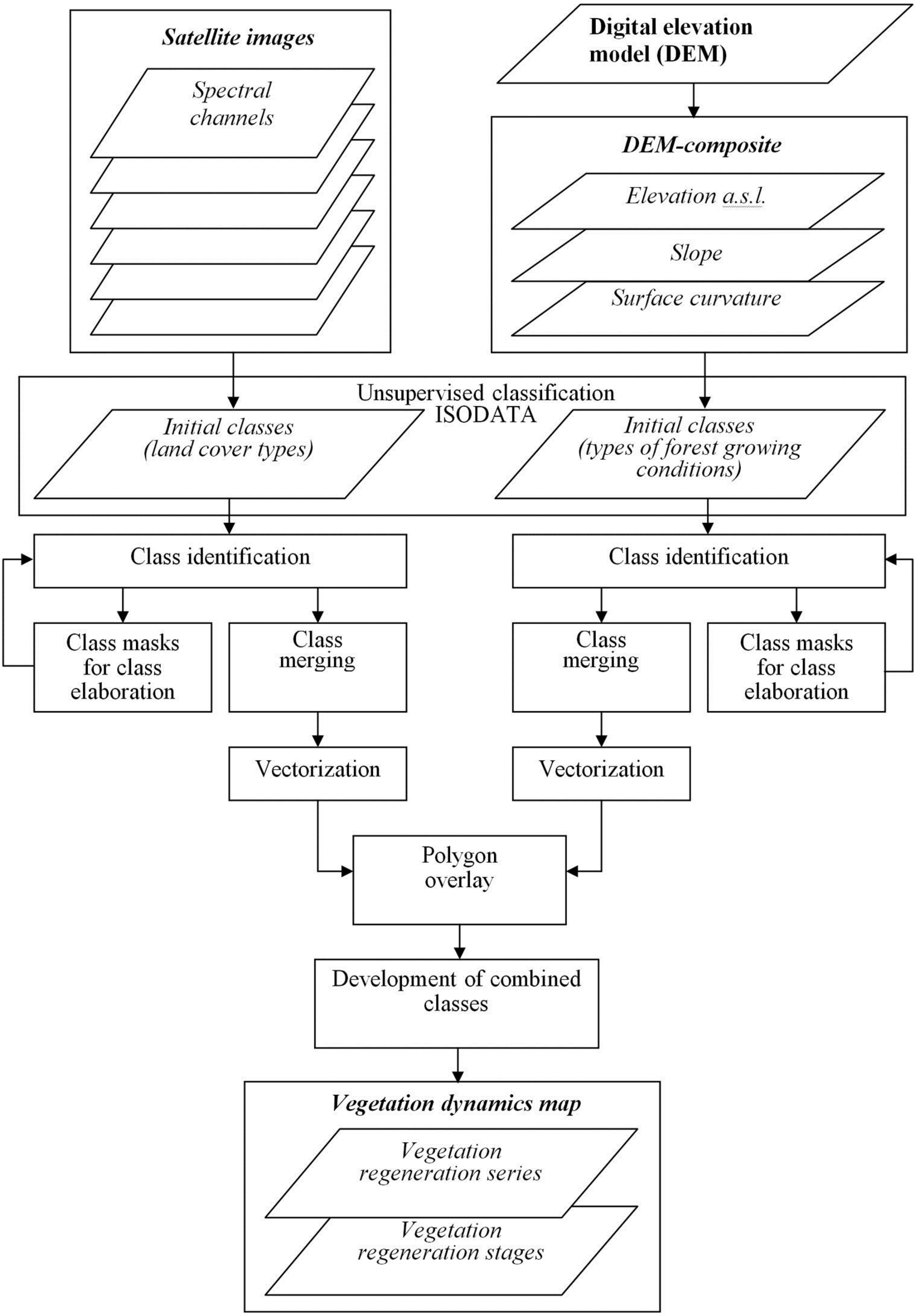

Fig.1. Flow-chart of the vegetation dynamics map development

The input data preparation included selection of Landsat TM/ETM images to cover the site of interest and their preliminary analysis for quality. Cloudiness masks and a mosaic of adjacent scenes (i.e. those with close acquisition dates) were made where necessary. The image acquisition dates (from June 15 to August 20) were selected to largely cover the growing season in central Siberia.

A raster layer of elevations above sea level was formed for the test site using the available digital models (e.g., SRTM 90) or through interpolating along elevation isolines, i.e. over elevation value networks, provided by paper topographic maps.

Satellite images were tied to these topographic base maps or to the basic raster mosaic of the available orthorectified (i.e., converted to the orthogolal projection) images (Landsat ETM mosaic, http://glcf.umiacs.umd.edu/data/mosaic/).

Raster layers of slope (S) and surface curvature (C) were formed based on the layer of elevations above sea level (H), when calculating additional DEM features. To simplify the following raster layer processing, H, C, and S values were stretched to cover a range of 0 to 255 and combined into a three-layer raster image (DEM-composite). The DEM-composite visualization in RGB colors provided a good picture of the orographic characteristics of the test site and allowed experts to do its visual interpretation.

The multi-band satellite and DEM-composite images selected were classified separately in an unsupervised manner (clustered) by ISODATA method (Richards 2005). This method is particular in that the selected desirable number of information classes should be greater than that expected to be finally obtained. We assigned 30 desirable classes before recognizing elementary land cover classes in Landsat ETM+ images, and 10 before the DEM composite classification.

The supervised classification method was not applied in our case, because choosing an adequate signature sample would be labor-taking with this method.

The initial classes obtained were analyzed and identified through comparing remotely sensed images, DEM, field data, forest inventory maps, and other available thematic maps. An excessive initial number of information classes presume that some of them should be united to make new classes. However, a necessity occurred in certain cases to divide certain classes into subclasses. In this case, reclusterization was performed for the selected image fragments determined from the classes that needed elaboration.

The raster layer of elementary land cover classes was obtained as a result of classifying and identifying satellite and DEM images separately.

The elementary land cover classes found based on satellite images were identified as the following forest regeneration stages: mature and overmature conifer stands; nearly mature conifer stands; mixed deciduous/conifer stands; young deciduous stands; and initial vegetation regeneration stages on logging and burned sites, with non-forest areas making separate classes. The raster layer derived from DEM data allowed us to identify landscape elements, such as slopes, river valleys, and flood plains.

In order to apply Kolesnikov's topogenetic approach the above maps were overlaid and their attributes were combined. As this is easier to do with vector maps, raster maps were converted into vector layers, which were then subjected to overlaying and a combined attribute table containing the names of the identified information classes was built.

The vector layer resulting from intersection was spatially generalized for removing small-sized polygons by adding them to their neighboring polygons along the longest common boundaries. The lower area limit of these small polygons was selected based on the initial raster image resolution and so that to ensure that the objects of the smallest possible sizes be reflected in a map of a desirable scale.

The output was a polygonal vector map containing attributes reflecting elementary forested and non-forest land cover classes supplied with descriptions of forest growing conditions associated with relief characteristics. New thematic groups, i.e., vegetation regeneration series, were formed from these description-tagged classes.

This methodology was used based on standard ERDAS Imaging and ESRI ArcGIS procedures to develop a vegetation regeneration map for the test site in the Low Angara region. Two geocorrected (i.e. converted into the orthogonal projection) 30-m-resolution Landsat ETM images taken on August 7 and 12, 2002, combined and cut along the test site boundary, as well as SRTM-90m DEM with 90-m pixel resolution (http://www2.jpl.nasa.gov/srtm/), were used as the input data. Each initial raster was converted into UTM (zone 46) projection, and then the rasters were superposed on fragments of forest vegetation maps and field sample site locations.

As a result, polygonal vector layers that show distribution of forest regeneration series and stages covering were obtained for a range of vegetation growing conditions the test site (Fig.2). The maps obtained showed current vegetation cover state. As the map legends were based on the topogenentic classification that shows site-specific forest vegetation development, these maps also enabled to predict dynamics of forest regeneration in different site conditions.

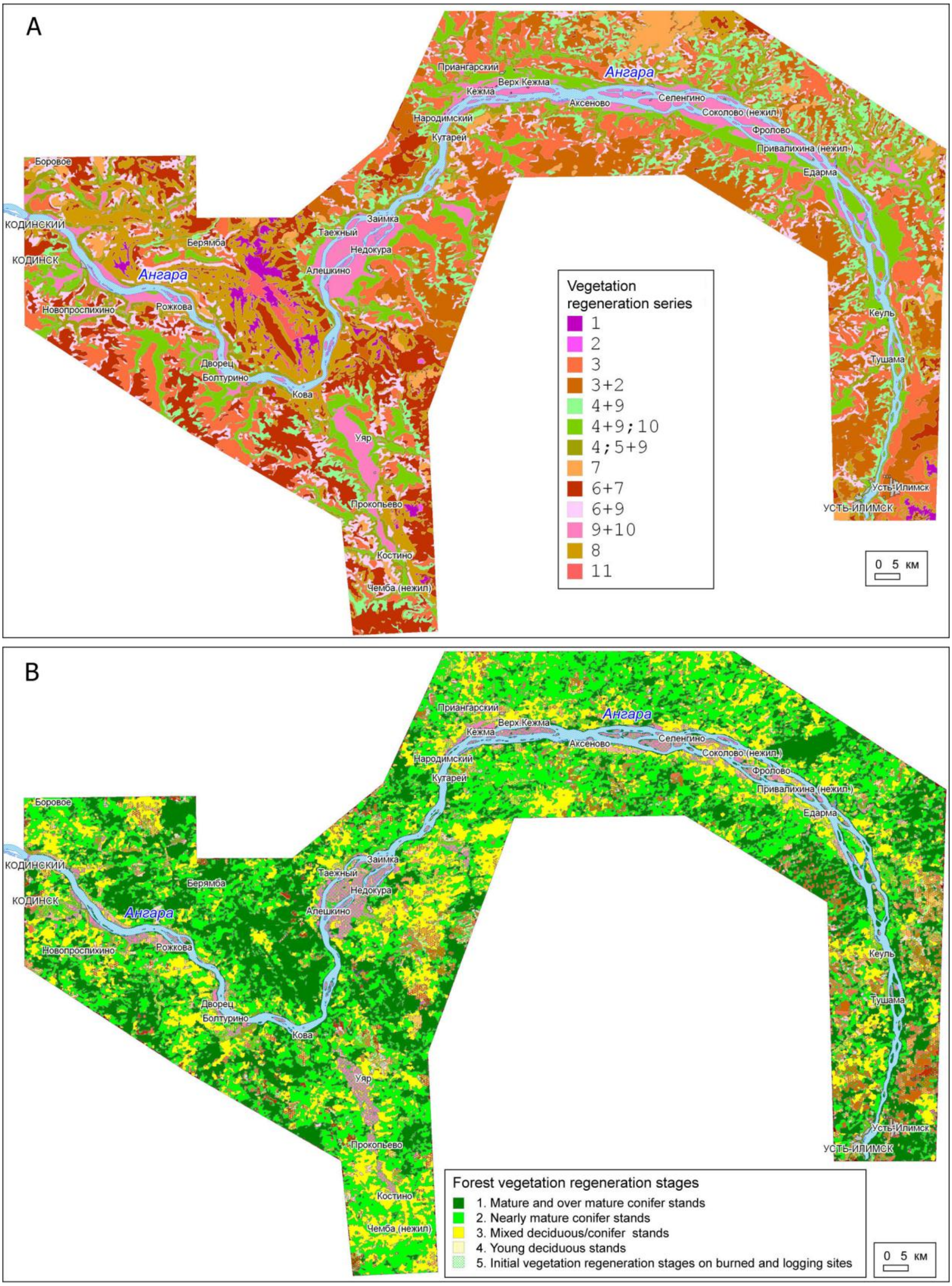

Fig. 2. Fragments of two layers of the test site forest dynamics map.

A – vegetation regeneration series. B – stand type (age stage) level.

A. The vegetation regeneration series:

1. Dark coniferous taiga forests on loamy soils of well-drained watersheds and slopes (450-520m a.s.l.). The major communities: mixed fir/spruce stands with ground vegetation constituted by feather moss and herbs. Secondary communities: birch stands with ground vegetation constituted by various herbs or feather moss and herbs. Site Class III.

2. Dark coniferous taiga forests on loamy soils and clay found in flat watersheds and on moist slopes (400-450m a.s.l.). Major communities: mixed Siberian pine/fir stands with feather moss as the ground vegetation. Secondary communities: mixed aspen/birch stands with tall herb/tall grasses, or various herbs/tall herbs ground vegetation. Site Class III.

3. Scots pine stands on loams in low flat watersheds and on soft slopes (250-300m a.s.l.). Major communities: Scots pine stands with minor components of larch and dark-needled conifers with ground vegetation constituted by feather moss mixed with herbs. Secondary communities: mixed birch/aspen stands with herbaceous or mixed herb/feather moss ground vegetation. Site Class III.

4. Scots pine stand on soils of light texture on soft slopes of river terraces (170-300m a.s.l.). Major communities: Scots pine stands with ground vegetation constituted by red whortleberry mixed with herbs or feather moss. Secondary communities: mixed birch/Scots pine stands with only herbs or feather moss mixed with herbs as ground vegetation. Site Class III.

5. Scots pine stands on sandy soils in watersheds and on high terraces of big rivers (200-250m a.s.l.). Major communities: Scots pine stands with ground vegetation constituted by whortleberry mixed with herbs, or pure whortleberry, or lichen mixed with whortleberry; these stands regenerate without woody species conversion, with the growing conditions promoting young Scots pine stands with pure dead needle litter, or dead needle litter/red whortleberry, or lichen/red whortleberry ground vegetation cover. Site Class IV.

6. Mixed Scots pine/larch stands on loamy and clay calcareous soils on soft and moderately steep slopes between rivers (300-350m a.s.l.). Major communities: mixed Scots pine/larch stands with ground vegetation constituted by feather moss mixed with herbs, or pure feather moss. Secondary communities: birch stands or mixed birch/aspen stands with only herbs, or tall herbs mixed with tall grasses, or various herbs mixed with tall grasses in the ground vegetation cover. Site Classes II and III.

7. Mixed Scots pine/larch stands on loamy and clay soils in the upper parts of slopes and on hill tops found in dome-shaped and hilly watersheds (350-400m a.s.l.). Major communities: mixed Scots pine/larch stands with feather moss and small shrubs in the ground vegetation cover. Secondary communities: birch stands with tall grass/herb, herb/feather moss, or herb/small shrub ground vegetation. Site Class IV.

8. Mixed larch/Scots pine stands on loams and clay on moderately and highly steep slopes between rivers (300-500m a.s.l.). Major communities: mixed larch/Scots pine stands with ground vegetation constituted by feather moss mixed with either herbs or small shrubs. Secondary communities: birch stands with only tall herbs or tall herbs mixed with tall grasses in the ground vegetation cover. Site Class IV.

9. Spruce stands on loamy soils in the lower parts of slopes lining river valleys. Major communities: spruce stands with a minor larch component with ground vegetation constituted by feather moss mixed with herbs. Secondary communities: birch stands with ground vegetation represented by tall herbs or tall herbs mixed with tall grasses. Site Class IV.

10. Bog spruces stands on alluvial soils in river flood valleys and on low river terraces. Major communities: spruce stands with ground vegetation dominated by grasses common in marsh. Secondary communities: birch stands with similar ground vegetation. Site Class IV.

11. Siberian Pine stands on loamy soils with crushed stone in highly elevated watersheds (>560m a.s.l.). Major communities: mixed Siberian pine/fir/spruce stands with mixed feather moss/small herb/small shrub ground vegetation. Secondary communities: birch stands with ground vegetation represented by tall grasses mixed with herbs, or herbs mixed with feather moss. Site Class IV.

B. The forest vegetation regeneration stages:

1. Mature and over mature conifer stands
2. Nearly mature conifer stands
3. Mixed deciduous/conifer stands
4. Young deciduous stands
5. Initial vegetation regeneration stages on burned and logging sites
6. Non-forest areas (including industrial lands and roads)

CONCLUSION

The methodology developed in this study is a step-by-step algorithm to identify forest cover units similar in the features set. The human factor involvement in thematic mapping was minimized by using methods of automated DEM and satellite imagery classification and GIS-based spatial analysis procedures. Combining automated methods with visual interpretation-based on expert estimates of the classes identified allowed us to identify forest regeneration series (the basic units of the topogenetic forest cover classification) and vegetation age stages. These are the two major forest regeneration dynamics characteristics, which, although indiscernible in satellite images, are vegetation thematic mapping targets. As this approach is relatively simple and can be implemented using different GIS software, such as ENVI, ERDAS Imagine, and IDRISI, it is can be widely used, modified and replicated.

The maps of the current vegetation condition obtained under our effort allow, as a part of GIS, to asses the current forest vegetation state and predict vegetation regeneration rates for a range of forest growing conditions. These maps are, in fact, spatial models that reflect the diversity of ecosystems encompassed by the test site and can be useful in sustainable forest management decision-making.

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