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Article

Mapping the current and past state of forest stands for the southern taiga of East Siberia

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Abstract: Maps of forest stand condition—the current phase of the forest-forming process—will be useful for foresters in their forest management in addition to the forest planning and cartographic materials. The mapping methodology was applied in the test area of the Bolshemurtinsky forest district of the Krasnoyarsk region, which is typical for the southern taiga forests of East Siberia. Source data for mapping was obtained on the basis of descriptions of the forest subcompartments on the GIS attribute table of the forest district. Forest stand confinement to the terrain relief indicators was identified on the basis of the SRTM 55-01 digital terrain model data. Spatial analysis has been performed using the ArcGIS Spatial Analyst module. Mapping capability has been shown not only for the year of forest inventory but also for the earlier period of time. To determine the predominant species and the age of the 100-year-old forest stand, a scheme was proposed in which the conceivable options are typified depending on the succession trend, the forest stand age prior to disturbance, and the period of reforestation. Map fragments of the test area as of 2006—the year of forest inventory—and as of 1906—the year of the intensive colonization beginning in southern Siberia—are demonstrated. Maps of forest condition in the test area represent successions that are typical in the southern taiga forests of Siberia: post-harvest, pyrogenic, and biogenic. The methodology of forest condition mapping is universal.

Keywords: forest-forming process; succession; forest district GIS attribute table; forest condition mapping

1. Introduction

Information about forest condition is the forest economic data, which allows obtaining analytical generalizations required for forestry. Visualization of the analysis results is achieved by using a mapping approach that enables monitoring of forest characteristics in statics and dynamics [1–3]. The geo-referenced aerospace images are used as a basis for mapping [4]. The achievable detail of forest inventory description of stands depends on the satellite equipment and the image scale.

Earth remote sensing data are used for the estimation and mapping of forest stands [5,6]. Zharko and Bartalev [7,8] have generated the map of the Russian forests featuring the predominant species using the MODIS satellite imagery (230 m). A more detailed forest classification, including dark coniferous, light coniferous, and mixed deciduous stands, was obtained on the basis of the Landsat data (28 m) [9–11]. However, subdivision of forest area into land categories or forest formations is evidently insufficient for forest inventory even according to the 3rd least detailed management type. The accuracy problem for forest inventory descriptions has been and remains relevant regardless of the inventory method.

This issue is not eliminated in relation to the image interpretation methods using multispectral satellite imagery [12]. Images of a higher resolution or even other ways of obtaining forest inventory data are more preferable for evaluation of the ground vegetation at the local level. For instance, data from lidar remote sensing of forest canopy allow automatic acquisition and mapping of forest stands with an accuracy sufficient for forestry planning [13,14]. An example of a step-by-step description of forest mapping using lidar imagery is cited by Novakovsky et al. [15].

The trajectories from the current forest condition (succession) to the future are indistinct; therefore, the foresters should elaborate a framework of adaptive management of future forests. Successions are the result of external impacts. Forest fires, harvesting, and forest pests are the most significant of them in Siberia. It is these external impacts that often interrupt the existing succession cycle, resulting in the dieback of the stands.

In forest management, it is important to understand not only the causes of changes but also the possibility of their visual analysis based on maps that reflect the phases of the forest formation process. Mapping clearly demonstrates the features of the transition from the past state of forests to the present. Maps of forest stand condition are an efficient tool for projecting future forests as well as substantiating current and future planning.

The purpose of our research is to develop a methodology for mapping the forest formation process phases. Our study was conducted in the test area of the Bolshemurtinsky forest district of the Krasnoyarsk Krai. Maps of forest condition were obtained as of 2006—the year of forest inventory—and as of 1906—the year of the active colonization beginning in southern Siberia.

2. Materials and methods

Forest inventory indicators of the forest stands are information that allow obtaining data for the climax species of the forest subcompartment, the type, and the trend of succession. At the moment in time, the condition of the forest stand is sufficiently fully characterized by the type and the trend of succession, the name of the climax species, as well as the name and the age of the predominant species. The GIS attribute table of the mass forest inventory contains specific forest information of forest subcompartments. The data for the climax species, the type, and the trend of succession should be additionally obtained. To achieve this, the description of the forest stands for the year of forest inventory is used: species composition, site index, and forest type, as well as spatial analysis of terrain relief indicators. The age of the predominant species of forest subcompartment specifies the current phase of succession explicitly. Spatial analysis of the relief is carried out on the basis of the digital terrain model (DTM) data.

2.1. Climax species determination

The predominant species are accepted as climax ones in coniferous stands. Birch and aspen forests are secondary stands replacing climax species at certain succession phases. The subtaiga zone is separated from the mountain-taiga zone by analyzing the confinement of pine and larch forest stands to the absolute elevations of the terrain.

Light coniferous forests (pine and larch) are accepted as the climax species in the subtaiga zone and dark coniferous forests (fir, cedar and spruce) in the mountain taiga.

2.2. Determination of succession types in the subtaiga zone

The beginning of mass forest exploitation in the Bolshemurtinsky forest district is associated with the beginning of intensive colonization of Siberia. In 1861–1905, about 1820 thousand people moved to Siberia, and 3040 thousand in 1906–1914 [16]. Selective cuttings were carried out in those years, which do not have distinct contours on the aerial and satellite images. The forest stand age is the only indirect indicator by which we can distinguish selective cuttings from dead stands. Assuming that intensive harvesting began in 1906, the pine forests of the subtaiga zone aged 70–100 years are mainly of post-harvest origin, and pine forests aged less than 70 years and more than 100 years are mainly of pyrogenic origin. Coenogenic successions are not characteristic of the light coniferous stands. For dark coniferous stands growing in river terraces of the subtaiga zone, coenogenic succession is determined by the different age of the dominant stand species. Forest pests do not lead to the dieback of the stands but only contribute to the thinning of stands and, as a result, the accumulation of fuel.

2.3. Determination of succession types in the mountain taiga zone

Clear-cutting is prohibited in the protected dark coniferous forests of the test area. Industrial harvesting is conducted in merchantable forests. The cuttings have contours defined well in the aerospace images that make them easy to identify. The forests are green and mossy; therefore, fires lead to the dieback of the stands in the summer-autumn period. To form the burnt area, a sufficient amount of fuel is required, which cumulates as a result of natural thinning (mortality), spring ground fires, outbreaks, and the fire transition within the soil. As a result of the Siberian silk moth outbreaks, dark coniferous forests die, and only then do the already dead forest stands burn down. It is impossible to reliably distinguish the pyrogenic or biogenic origin of a dark coniferous stand according to the forest inventory descriptions. Considering the high humidity of the sites in the mountain taiga zone, biogenic origin is more likely. All types of successions are characterized by reforestation with a change of species to birch and aspen.

2.4. Mapping of forest stand condition

The “PRESENT” field is created in the GIS attribute table, which combines information about the age of the predominant species of the forest subcompartment, the climax species, the type, and the trend of succession. Mapping of the condition of forest stands as of the year of forest inventory is carried out by the data of the “PRESENT” field. To map the forest condition as of 1906, it is required to project the characteristics of the forest subcompartments of 2006. The “PAST” field is created in the GIS attribute table, which contains information on the predominant and climax species, the type, and the trend of succession. Mapping of the forest stand condition is conducted according to the data of the “PAST” field.

3. Results and discussion

The mapping methodology is applied in the test area in the southern taiga forests of the Bolshemurtinsky forest district of the Krasnoyarsk region. The area is 14,724 hectares (804 forest subcompartments). The Bolshemurtinsky forest district is located in the southern taiga district of the Yenisei Mountain Forest Province. The mountains of the Yenisei Ridge create an environment for the formation of high-altitude zones (belts) of subtaiga pine and mountain-taiga dark coniferous forests. The Yenisei Ridge intercepts atmospheric precipitations, so the forest stands of the mountain taiga belt are relatively humid.

The forests of the Bolshemurtinsky forest district have long been exploited. In earlier times the subtaiga pine forests were harvested by selective cuttings, including water protection forests along the Yenisei River, where 70-80-year-old pine and larch stands grow now. In the dark coniferous plantations of the mountain taiga zone, intensive forest exploitation began only in recent decades.

The forest type is an indicator of the trend of succession. Successions of pine forests are pyrogenic and post-harvest. Successions of the dark coniferous forests are biogenic, pyrogenic, and post-harvest. The test area is located within the trapezium of the SRTM 55-01 DTM. A combined raster of the test area was obtained by combining the channels of the altitude raster and exposures.

A pine is accepted as the climax species in the subtaiga zone according to the following criteria: the absolute altitude does not exceed 280 m; the slope exposure is 135°–315°; a pine is present in the forest stand and the undergrowth. A spruce and a cedar are accepted as the climax species according to the confinement of the forest stands to watercourses—according to the forest types of floodplains and river terraces.

In the mountain-taiga zone, fir and cedar are taken as the climax species to the following criteria: the absolute altitude exceeds 280 m, the locations are watershed areas, and the low-gradient slopes of the valleys. Spruce is taken as a climax species according to the confinement of forest stands to watercourses—by the forest types of floodplains and river terraces.

The proportion of coenogenic successions can be approximately estimated by representation of all-aged forest stands. Falaleev concludes that the Siberian forest stands are mainly all-aged. In contrast, the mass data of forest inventory record the predominance of the even-aged forest stands. Thus, scientific assessments of the age structure of forest stands differ substantially. As a whole, it can be affirmed that the age diversity of the dark coniferous stands is greater, and the presence of dark coniferous species in the forest stand increases the possibility of coenogenic succession.

Forest fires are the most significant environmental factor in the southern taiga, determining the species composition, the storied structure, and the age structure of forest stands. The current vegetation cover is largely a result of the interaction between the spatial and temporal dynamics of large fires and physical, geographical, and climatic conditions. The light coniferous forests are widely represented only as a result of forest fires in Siberia. It has been argued that the pine forests of the Angara region exist precisely because of forest fires.

Forest stands of the southern taiga are the most productive and accessible for the intensive industrial exploitation. The choice of the cutting method correlates with the projection of subsequent reforestation. The reforestation of cutting areas is ensured by assisted natural regeneration, provided that the cutting practice rules and the technological process of forest harvesting are followed. In practice, this condition is often not fulfilled. For instance, there is a change from the coniferous to the soft-leaved species in 57% of cutting areas in the Angara region despite the favorable forest growing conditions. Digression processes—such as bogging up and sod formation—continue in parts of the cutting areas. Forest plantations have been developed in such cuttings and this also does not always lead to the desired result.

The substantial damage of the southern taiga forests is caused by the needle- and leaf-eating insects, among which the Siberian silk moth holds a special place. The destruction of forests by these pests during the breeding outbreaks is comparable in scale to the forest destruction caused by fires and industrial logging. The caterpillars of the Siberian silk moth destroy the needles of dark coniferous trees. The forest stand dries out and falls out partially, forming a deadfall. As a result, secondary zoo- and phytopests appear numerous. An example is the dieback of the forest in the Ket-Chulym interfluve area, where the dark coniferous taiga dried off in an area of 1.5 million hectares as a result of the Siberian silk moth outbreak in 1952–1957. In general, the outbreaks of the Siberian silk moth occupy an area of about 800 thousand hectares in Krasnoyarsk Krai [17]. The fire hazard increases dramatically in these areas. A large amount of forest fuel provides a high-intensity forest fire. Post-fire reforestation proceeds the same way as in burnt areas—by coppice growth of a birch, an aspen, and border seeding.

Currently, there is no usually accepted theory of forest successions. On the contrary, a difference in opinions could be observed. The scientific school of the authors, the originality of methodological approaches, as well as the inconsistency of terminology, determines the diversity and often incompatibility of the known classifications of forest successions. We abide by the scheme developed by Shvidenko as part of the project named "Forest resources, environmental problems, and socio-economic development of Siberia" [18]. The scheme contains the main characteristics of forest successions: origin, geography, and sequence of changes in the species composition of the forest stand; and it provides the possibility to determine the duration of phase and age stages of successions (scheduling) by types of ecological modifications of forest formations [19]. The scheme has been significantly simplified relating to the object of forest stand mapping. Climatomorphogenic successions have been excluded. Zoogenic and pathogenic successions are considered together and named as biogenic ones. The types of coenogenic successions as well as the trends of pyrogenic and anthropogenic successions are combined.

The results of forest stand mapping as of 2006 and 1906 are shown as in the case of the test area (**Figures 1** and **2**). The visibility of changes over the past 100 years is achieved due to the possibility of visual comparison with the map of the forest stand conditions as of 2006. The mapping legend as of 2006 is framed in the form of a sequence of symbols. For instance, the record C(C)_31_110 means a pine forest stand, the climax species is a pine of pyrogenic origin without species replacement, the age of the pine stand is 110 years. Codes of successions include: (1) biogenic; (2)

coenogenic; (3) pyrogenic; (4) anthropogenic. The trend of successions is the following: (1) without species replacement; (2) with species replacement.

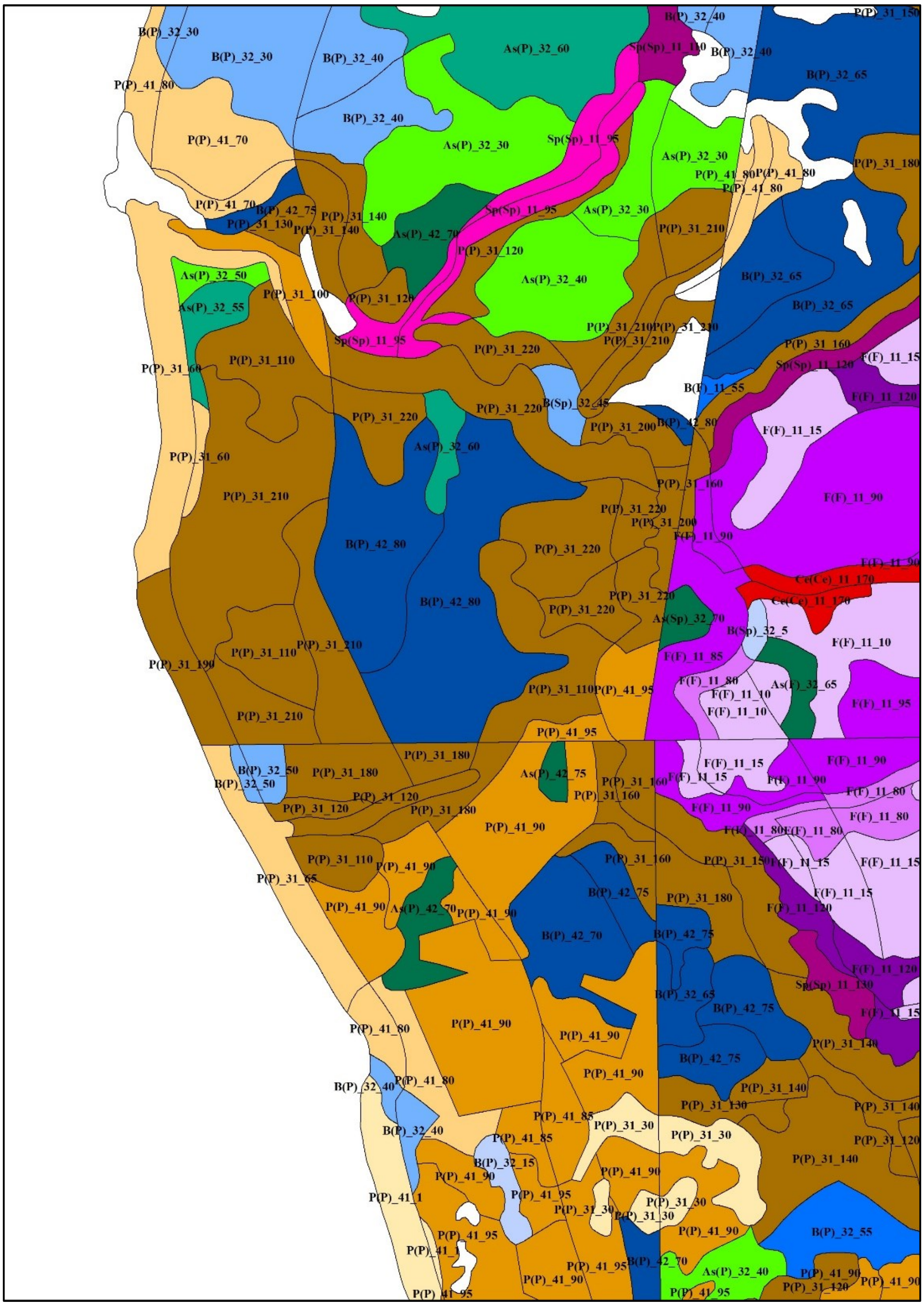

Figure 1. Predominant and climax species, type and trend of succession, age of the forest stand as of 2006 (a map tile of the test area).

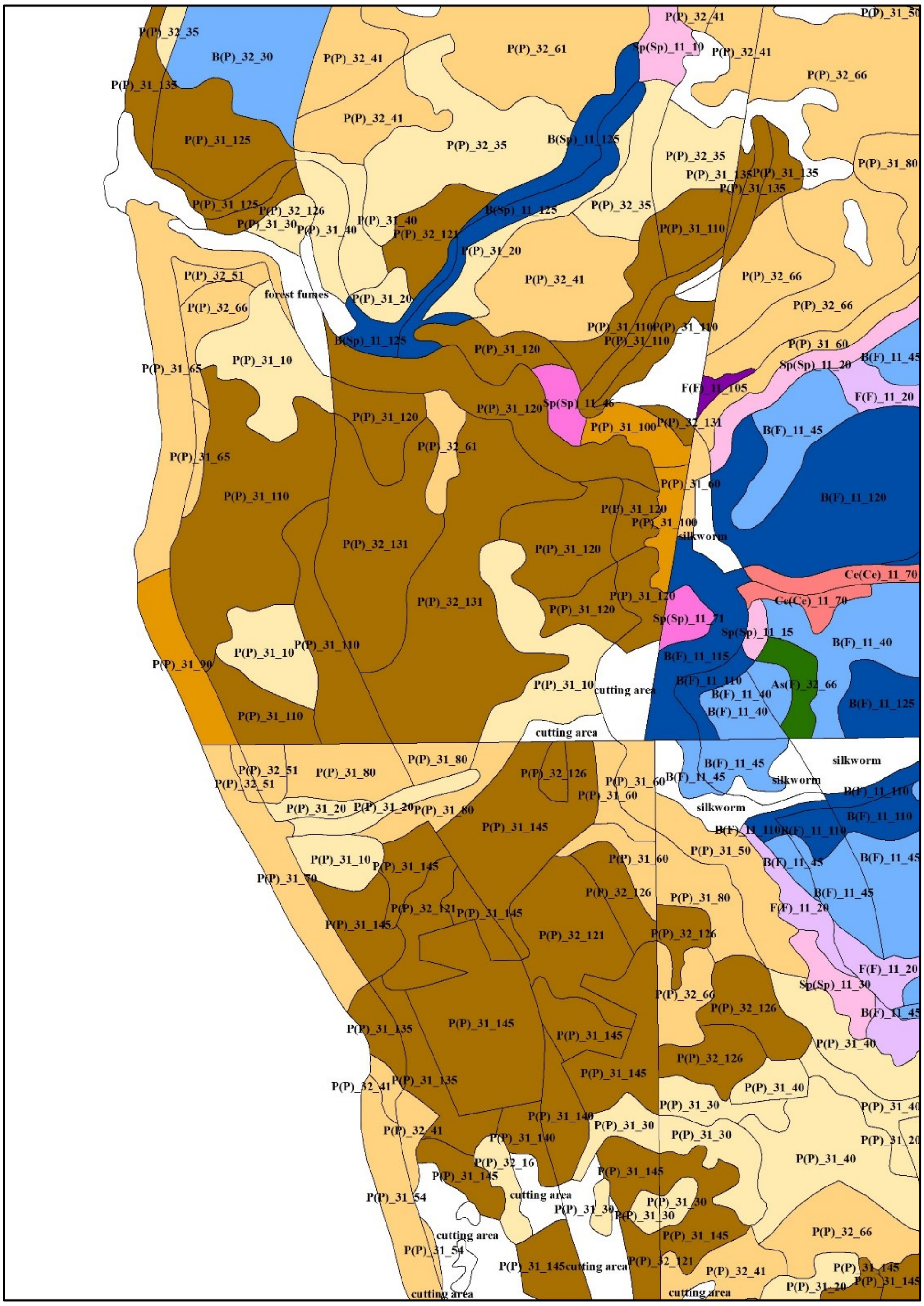

Figure 2. Predominant and climax species, type and trend of succession, age of the forest stand as of 1906 (a map tile of the test area).

When filling in the "PAST" field with data, the same trend of succession is accepted—succession with or without species replacement for both post-harvest and post-fire forest stands. Configurations, areas, and characteristics of forest subcompartments within non-forested areas have not been changed as of 1906 and 2006. It has also been taken into account that under the forest-growing conditions of the Bolshemurtinsky forest district, hardwoods (birch and aspen) regenerate following forest fires and harvesting in 1 year; pine and larch—in 5 years; spruce, fir, and Siberian pine—in 10 years. Reforestation of the areas damaged by the Siberian silk moth occurs with species replacement and takes about 20 years [20].

The result of reducing the age of the forest stand (A) by one hundred years ($A - 100$) could take a positive, negative, or zero value.

Only the age of the forest stands changes with a positive value of A ($A - 100 \geq 0$), i.e., 100 years less. In such cases, recording the forest stand condition is straightforward. For instance, if the Siberian pine of biogenic origin (following an outbreak) is 220 years old, the climax species is the Siberian pine, then the record as of 2006 is K(K)_11_220. The record as of 1906 is K(K)_11_120.

With a negative value of A ($A - 100 < 0$), the forest stands should be restored as for 1906. This requires the age of the forest stands prior to disturbance of A_0. Selective cuttings were carried out at the age of quantitative maturity. For pine forests, the age value (A_0) of 150 years is accepted; 150 years for spruce forests, and 130 years for fir forests. It is impossible to identify the age of the dark coniferous forest stand prior to its damage by the Siberian silk moth as well as the age of the birch and aspen forests that are regenerated following outbreaks. Therefore, the A_0 value of 130 years is assumed regardless of the predominant species of the forest stand.

The calculation of the forest stand age is made for 1906 according to the dependence $A_{1906} = A_0 - x$, where $x = 100 - (A + \text{n})$. Some examples are cited below:

1) The post-harvest pine forest stand is 95 years old. Pine is the climax species. The condition record as of 2006 is C(C)_41_95. This means that x is equal to 0 and forest harvesting was carried out in 1906. The record of the forest stand condition as of 2006 is "CUTTING AREA".

2) It is the spruce forest stand damaged by the Siberian silk moth. Spruce is the climax species. The condition record as of 2006 is E(E)_11_95. Reforestation of the damaged area occurs with a change to the secondary birch and aspen forest stands. This means that x is equal to 5, and the age of the birch forest was $A_0 = 130 – 5 = 125$ (years) in 1906. The record of the forest stand condition as of 1906 is B(E)_11_125.

3) The post-harvest pine forest stand is 90 years old. The climax species is pine. The record is C(C)_41_90. This means that x is equal to 5 and the pine forest stand had a pyrogenic origin prior to forest harvesting. The record of the forest stand condition as of 1906 is C(C)_31_145.

4. Conclusion

The development of forest management plans is multidimensional and is justified by the probable directions of the forest formation process, among others. Managerial decision-making is based on raw data. The data of forest stand-level inventory and forest planning are used as raw data in the practice of the forest company. Presently, this is the most complete and reliable forest information that is ideal for thematic forest mapping in a format of the GIS tabular representation. Potential alternative information obtained with the satellite imagery has not yet been able to compete with mass forest inventory data. The amount of land cover recognition methods increases, but the compilation of accurate maps remains a challenging issue.

Mass forest inventory data, as presented by spreadsheets, are convenient for mathematical and spatial analysis and allow obtaining advanced research and practice results. For instance, the damaged forest cover could be established over a certain period of time, or valuation of forest stands could be put on. Such information support is important for balanced management decisions.

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