Automatization of forest ecosystems sustainability estimation based on complex modelling and Earth observation data

V Zelentsov1*, O Brovkina1,2, I Pimanov1, S Potryasaev1

1Laboratory of Information Technologies in System Analysis and Modeling, St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences, 14-th Line of Vasilyevsky Island 39, St. Petersburg 199178, Russian Federation
2Department of Remote Sensing, Global Change Research Institute CAS, 986/4a Bělidla, Brno 60300, Czech Republic

*Corresponding email: v.a.zelentsov@gmail.com

Abstract. The paper considers methods and information technologies for full automatization of forest ecosystems sustainability estimation. Analysis of forest ecosystem sustainability is explored as a multi-objective problem with applying a complex of models for calculating partial indicators of sustainability. Earth observation (EO) data is used as an essential component of information support for estimating forest ecosystems sustainability indicators. Methodological framework of automatization consists of complex modelling, application of models qualimetry methods for selecting specific calculation models, and methods for multi-criteria analysis to estimate generalized indicators of sustainability. A software architecture is proposed in order to implement procedures of complex modelling with integrated processing EO and field data.

1. Introduction

The concept of forest ecosystem sustainability has been a focus of modern forest management for over two decades [1, 2]. The ecosystem sustainability definition has been expressed as a capacity of ecosystems to maintain their essential functions and processes, and retain their biodiversity in full measure over the long-term [3]. Its criteria covered are: social and economic function and condition, productive capacity, ecosystem health and vitality, soil and water protection, carbon cycle and biological biodiversity [4] (figure 1). Approaches to measure forest sustainability and assess its status are introduced at the global, national and regional scale [5-8].

At the same time there is a generally admitted fact that in order to evaluate forest ecosystems sustainability it is required to apply a variety of partial indicators and thus – a big set of diverse models of forest phytocenosis functioning, while each model can be applied for estimating its partial indicator of sustainability or a complex of indicators [8-13], as well as to apply different types of ground and remote sensing data for computation [14-16]. Thus, at least two major aspects should be taken into consideration in automatization of forest ecosystems sustainability estimation.

The first aspect implies that the key feature of the considered tasks is their multimodel and multi-criteria nature. This leads to uncertainty, related to complex codependency among various partial indicators of sustainability and necessity to evaluate and select specific models to estimate these indicators. Additional complexity is the need to analyze a set of indicators in dynamics, reflecting the processes of structural changes within the process of forest ecosystems functioning, including the influence of perturbing factors. These factors complicate integrated estimation of forest ecosystems...
sustainability and complex automatization of this task. At the same time a number of works [17-22] demonstrates that forest ecosystems functioning and development is based on common system-cybernetic patterns and can be reasonably described using controllable dynamic models. In this view, in order to overcome uncertainty related to multimodel and multi-criteria nature of the tasks on estimating sustainability of forest ecosystems, development and adaptation of results, received within such modern directions of the system-cybernetic fields as the theory of managing structural dynamics of complex systems qualimetry of models and polymodel complexes [23] become of the major importance.

Figure 1. Key criteria of forest ecosystem sustainability (*according to [24]).

The second aspect is related to informational support of the addressed tasks. Currently, Earth observation (EO) data play a more and more significant role within analysis of forest ecosystems over the huge territories of forestland. Remote sensing measurements provide a valuable additional, and sometimes – for the big territories – the only one source of information of forest ecosystems' structures and their dynamics. The contribution of EO data to sustainability indicators estimation is provided in figure 1.

Satellite-based multispectral imaging spectroradiometers, such as NASA’s Landsat program, offer a unique opportunity to study a long-term development of forest ecosystems through the availability of long-term data series (since 1970s) [25]. ESA satellite Sentinel-2 (since 2015) has considerably improved monitoring capabilities by spectral and spatial resolution compared to Landsat and is most relevant to analyse recent spatial and temporal changes in forest ecosystems [26]. Airborne and unmanned aerial vehicle (UAV) imaging spectroscopy provides hundreds continuous narrow spectral bands allowing to describe diagnostic absorption signatures and biochemical differentiation [27]. Airborne laser scanner has been recognized as an important data source for studying a forest ecosystem structure and above-ground biomass [28].

Currently, big archives of EO data have been collected, and, combined with materials of the permanently implemented ground measurements, that forms conditions for analysis of forest ecosystems sustainability in dynamics. Nevertheless, from the point of automatization it is required to further develop methods for estimating indicators of forest ecosystems sustainability based on EO data processing, as well as, at first instance, on the basis of integrated processing of remote and ground measures materials. For integrated processing it is necessary to provide unification and joint analysis of heterogeneous data, received from field, aircraft and space sensors, expert knowledge on the observed processes and objects, as well as data on the major factors that influence changes of the forest ecosystems
conditions – climate, anthropomorphic etc. Unlike existing unified data processing systems [17], our study approach suggests processing diverse data and estimating indicators of forest sustainability within unified information automated system (IAS). This will ensure integration of both heterogeneous data and models for assessing sustainability of forest ecosystems, as well as provide geoinformation tools for visualizing results of the analysis in the form of dynamic digital maps.

2. Methods and Materials
The suggested approach to automation of the forest ecosystems sustainability estimation includes:
- estimation of partial sustainability indicators based on integrated use of field measurements and EO data,
- methods of multi-criteria analysis and models selection for calculating the generalized indicators,
- architecture of the unified information system, developed for complex modelling and analysis of forest ecosystems sustainability.

2.1. Indicators for forest ecosystem sustainability estimation from EO data
The proposed approach focuses on those forest ecosystem sustainability indicators that can be directly observed or inferred from EO data (Figure 1). The preliminary set of indicators, which can be estimated based on remote sensing methods is provided on the table 1. Figure 2 shows the position of indicators within the whole procedure of estimating forest ecosystem sustainability.

Table 1. Preliminary set of indicators for forest ecosystem sustainability estimation to be extracted from EO data.

| Criteria                          | Indicator                                                                 | Definition                                                                 | Method from Remote Sensing                                                                 |
|-----------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Biodiversity                      | Fragmentation of forest                                                   | Information on the extent to which forests are being fragmented over time by human activities and natural processes | Crown density estimation, classification of land-use land-cover                         |
|                                   | Number of native forest associated species                                | Information about tree species composition                                 | Tree species classification                                                              |
| Productive capacity (partly)      | Changes in the productive capacity of forests                             |                                                                           | NPP (net primary production), Exergy of solar radiation, Sunlight use efficiency, AGB (aboveground biomass) estimation |
| Health and vitality               | Biotic processes and agents in the forest                                 | Area and percent of forest affected by disease, insects, invasive species  | Vegetation indices (VIs), Composite indicator of (spruce) forest health, LAI             |
|                                   | Abiotic agents in the forest                                              | Area and percent of forest affected by fire, storm, land, clearance       | Image texture analysis, VIs, Ecological integrity, LAI                                   |

*according to the resource data [4]
2.2. Complex modelling methods

In order to apply system-cybernetic methods for analysis of forest ecosystems sustainability it is crucially important that forest phytocenosis have several types of structures – a species composition structure and a spatial structure (vertical and horizontal structures) [29]. This defines efficiency of applying the recently developed methods of the theory on complex objects structural dynamics, which assume unified analysis on functioning of several types of structures, using the concept of multi-structural macro-state of complex system [23]. Thus, the possibility to perform multi-aspect analysis of sustainability, based on the unified methodological approach is implemented.

One of the key problems of applying multi-criteria methods for analysis of forest ecosystems sustainability using a complex of models – is the problem of estimating models quality, analysis and ranging different classes of models, justified synthesis of new models, or selection the most preferable models from a number of already existing ones, aimed at solving exact applied tasks for estimating some or other sustainability indicators. The scientific and methodological basis for automatization of multi-criteria selection of models is the above mentioned approaches, developed within qualimetry of models and polymodel complexes [24].
Estimation of required adequacy of modelling takes a special place in solving the problems of modelling complex objects $O_{b_{c>}}$. Obviously, it is necessary to evaluate how adequate it is in relation to the $O_{b_{c>}}$ every time. Inaccurate initial assumptions in determining the type and model structure, error measurement in the test (experiment), computational error in the processing of measurement information could be the reasons for the inadequacy of the $O_{b_{c>}}$. Using an inadequate model can lead to significant economic losses, and to the default tasks of the actually existing system.

In accordance with the qualimetry of models, there are two classes of simulated systems [24]. The first class consists of the systems with which an experiment (test) can be conducted and received by measuring the values of the system characteristics. The second class of simulated systems are the systems on which it is impossible to conduct experiments. The ecosystem sustainability analysis systems discussed in this article are a good example of first-class systems. Figure 3 represents the generalized technique for estimating and controlling the quality of models in this case [22].

![Figure 3](image.png)

Figure 3. The generalized technique for estimation and control of the first class models quality.

2.3. IAS architecture

Today, there exists a lack of information systems that could be adapted for a user without specialized skills in information technologies and EO data processing. This gap becomes a significant obstacle to wider use of accumulated and steadily growing volumes of EO data and contemporary models for forest ecosystem sustainability assessment.

In order to solve these problems, information systems of a new level are required. These systems are to be aimed at integration of EO and other data (both spatial and non-spatial) with models of forest state assessment, in automatic mode. As mentioned above, a theoretical foundation for such systems creation is provided by methods of a new scientific direction - qualimetry of models and polymodel complexes [24]. This theoretical basis enables embodying the intellectual multi-criteria choice of models required for making the right decision and adjusting models parameters without operator’s intervention. Along with that, contemporary information technologies open up new opportunities to design and operate distributed systems. Conjunctive usage of these achievements has led to creation of an information automated system based on a service-oriented architecture (SOA). A general structure of the proposed IAS is provided in figure 4.
Figure 4. The IAS general structure.

Main units ensuring interaction of IAS components are as follows: a service bus, as a “backbone” of the platform’s architecture; business process execution language (BPEL) [30, 31] tools to implement components interaction scenarios; an intellectual interface for choosing particular models of forest ecosystem sustainability components (productive capacity, fragmentation of forest, etc.) and adjusting their parameters in automatic mode; program interfaces and wrappers to ensure interconnection of diverse modules as web-services; a user interface enabling easy access to the IAS running results.

3. Conclusion
Estimation of forest ecosystems sustainability in the general formulation is a multi-criteria task that requires using ground measurements and Earth observation data. This study offers a constructive approach to automatization of forest ecosystems sustainability analysis, based on methods of multi-criteria analysis, management of complex systems structural dynamics, qualimetry of models and polymodel complexes, as well as modern information technologies. This approach can be implemented in practice by information and analytical system, based on SOA to automate the processes of multimodel analysis for forest ecosystems sustainability.

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