A COMPLEX MODEL FOR FOREST ECOSYSTEM STATE ASSESSMENT BASED ON REMOTE SENSING DATA: CASE STUDY IN BAIKALSKY NATURE RESERVE

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ABSTRACT
This study describes a complex model for forest ecosystem state assessment in the Baikalsky Nature Reserve based on multispectral satellite and hyperspectral airborne data. The objective of the study is to estimate ecosystem stability, degree of anthropogenic load and the relative tension index of the environmental situation on the study territory. Results demonstrate the average sustainability of 0.8 (middle to high level) and an anthropogenic load of 0.3 (middle level). The ecological situation is estimated as satisfactory. The degradation of conifers indicates a decrease of protective functions of the ecosystem. Our proposed methodology for forest ecosystem state assessment is based on remote sensing data and can be potentially useful for regional and large-scale forest monitoring and management.

Keywords: forest ecosystem, satellite data, hyperspectral airborne data

1. INTRODUCTION

The application of modeling in ecology allows the prediction of the behavior of complex systems to which forest ecosystems belong (Scheller & Mladenoff 2007). Currently, forestry studies have demonstrated the beneficial approaches of modelling based on remote sensing (RS) data taking into account the growing condition, species composition, forest management arrangement, physical-geographical characteristics, and the size of the specific forest site. These models using RS data have been applied in variety of forest studies: terrestrial carbon cycling (Turner et al. 2004), forest decline (Lambert et al. 2013), biodiversity (Wang et al. 2010), forest structure (Gomez et al. 2012, Sokolov et al. 2014) and aboveground biomass (Lu et al. 2014; Brovkina et al. 2015).

A complex estimation of the functioning of a forest ecosystem has been less investigated using RS data-based modelling. Ravan et al. (1997) analysed the state of a forest ecosystem estimating the impacts of disturbance on forest structure using satellite RS in the Madhav National Park of India. Balenović et al. 2015 estimated and forecasted forest ecosystem productivity by integrating field measurements, RS, and modelling, on an oak forest (Quercus robur L.) site in Croatia. A number of complex forest biophysical parameters are considered to estimate the state of the forest ecosystem using RS data in Zawadzki et al. (2005). The application of solar radiation exergy is described as a tool for ecosystem health assessment in forest ecology, especially in the fields of ecological modelling (both mathematical and physical) in Jorgensen & Svirezhev 2004, and Silow & Mokry 2010. The ecosystem exergy represents the maximum energy capacity to perform useful work as the system proceeds to equilibrium, with irreversibility increasing its entropy at the expense of exergy. Taken by itself, the total exergy of an ecosystem is a measure of the change in entropy content from the equilibrium and the actual state. Differences in exergy for the past 20 years were estimated and compared with differences in biodiversity and biomass in Chinese eucalyptus plantations (Lu et al., 2011). Rosen (2002) confirmed that the biggest asset of forest ecosystem exergy analysis is that it can measure the disorder increase in ecosystems associated with human environmental impact.

The forest ecosystem of the Baikalsky Nature Reserve is a reference territory for assessing the impact of industrial air emissions of Southern Siberia. One of the most important missions of the Baikalsky Nature Reserve is to protect undisturbed cedar forests. Since 2007, a decline in forest processes has been observed in the Baikalsky Nature Reserve caused by global climate change, air pollution, insect pests and bacterial dropsy damage (annual report of Federal Forestry Agency of Russia, 2014; Belova, Morozova 2016). Nowadays, complex estimation of forest ecosystem state is a critical and relevant task. This study was initiated to develop a complex model for a forest ecosystem state assessment in the Baikalsky Nature Reserve based on RS data. Specifically, the objective of the study was to estimate ecosystem stability, the degree of anthropogenic load and a relative tension index of the environmental situation on the forest territory of the Baikalsky Nature Reserve.

2. METHODS

2.1. Study area

The study area is comprised of the Baikalsky Nature Reserve located along the southern coast of Lake Baikal in Russia (Fig. 1). Several forest species prevail in the study area: birch (Betula platyphylla Sukaczev), cedar (Pinus sibirica Du Tour), fir (Abies sibirica Ledeb.) and spruce (Picea obovata Ledeb.).

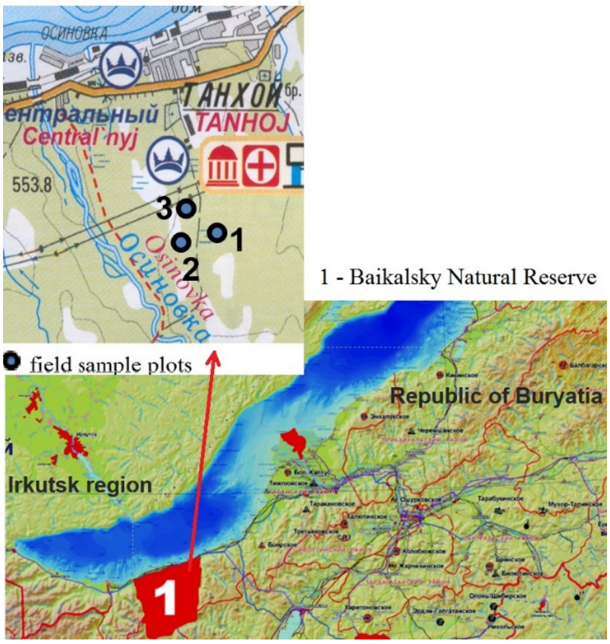

Figure 1: Location of the Baikalsky Natural Reserve and field sample plots

2.2. Data

Hyperspectral data in the spectral range of 400 – 900 nm with a spatial resolution of 0.4 m was acquired by an unmanned aerial vehicle (UAV) in June 2015. Pre-processing of hyperspectral data included radiometric, geometric and atmospheric corrections. Radiometrically corrected satellite scenes from Landsat 5 and Landsat 8 were downloaded from the U.S. Geological Survey data portal for the vegetation period of 2015 (http://earthexplorer.usgs.gov/). Atmospheric correction of satellite data was achieved with the FLAASH module of ENVI 5.1. Field data included sample cedar plots (3 plots) where the health status category of cedar was estimated (Table 1).

Table 1. Cedar health status of sample plots in 2015

Sample plot	Age class	DBH [sm]	N of trees	Health status category
1	IV	33	98	III
2	III	30	141	III
3	III	28	157	I - II

Health status category: III – highly weakened, IV – drying, V – deadwood. Age class: III – 120 years, IV – 160 years.

2.3. Complex model for assessment of forest ecosystem from RS data

The complex model for assessment of forest ecosystem was based on a separation of the study area to the degree of anthropogenic intensity (I) (Mochalov et al. 2015). Where I is an evaluation of the ecosystem's balance estimated from the degree of anthropogenic load, R, and potential sustainability, S: good (< 0.2), satisfactory (destruction of sensitive species) (0.2..0.5), tense (structural changes) (0.5..0.8), crisis (0.8..0.9), and catastrophic (destruction of the ecosystem) (> 0.9).

$$S = (AGB*NPP) / Ex, \quad (1)$$

$$I = R/ S, \quad (2)$$

where NPP is net primary productivity.

The degree of anthropogenic load was expressed as a sum of the ratio of the decline of the treed area, Sa, to the total forest area for each species, Sf.

The sustainability of forest ecosystems is an important indicator of the ecological state of the territory and characterizes the adaptive capacity of the ecosystem to identify and project anthropogenic load. This sustainability represents the fraction of absorbed solar radiance that can perform useful work, which is used for biomass accumulation in forest ecosystems and to ensure its productivity. S was determined based on the estimation of aboveground forest biomass, AGB, and solar radiation exergy, Ex, as indicators of the ecosystem state.

The technology of complex modelling included the classification of forest species, aboveground biomass estimation; detection of forest decline and the assessment of ecosystem state indicators (Fig. 2).

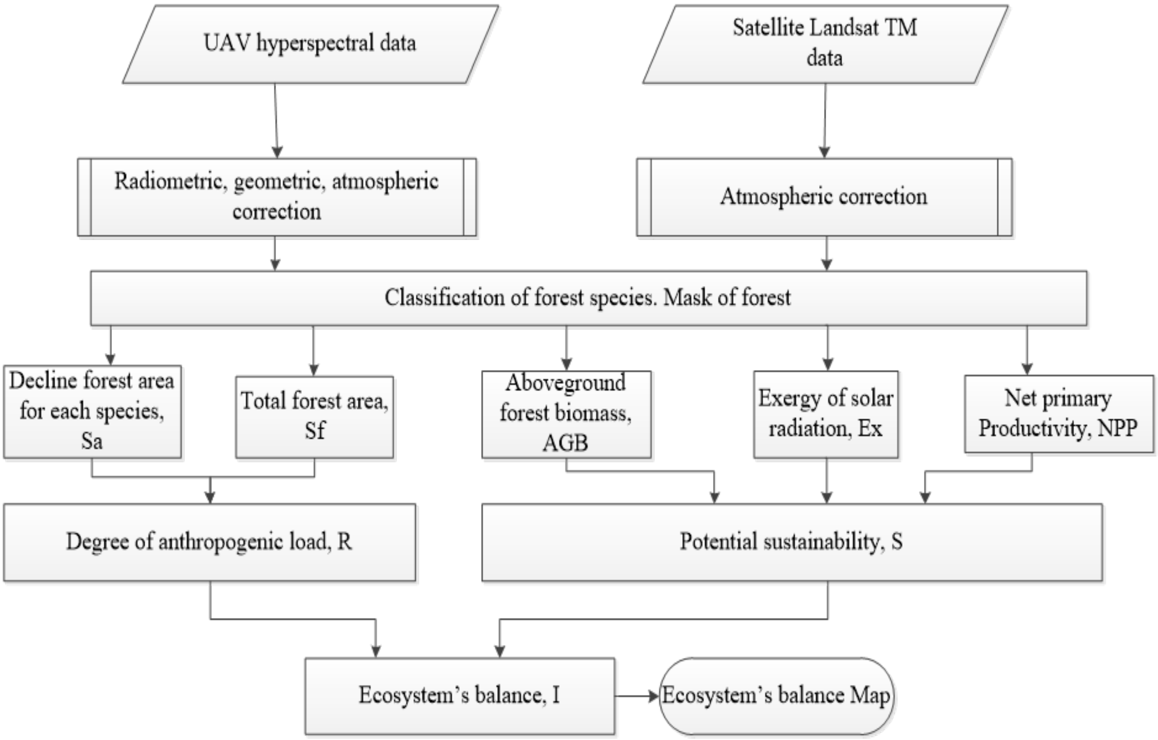

Figure 2: Framework of the technology of complex modeling for forest ecosystem state assessment

One of the main distinguishing features of the technology is the integrated processing of UAV hyperspectral data and satellite data while modelling (Sokolov et.al. 2012, 2014, 2015; Zelentsov et al. 2013, 2015).

2.3.1. Classification of forest species

The Spectral Angle Mapper method was used for the classification of forest species. The forest mask was obtained using the normalized difference vegetation index (NDVI) and near-infrared reflectance values. The accuracy of the classification result was estimated by the calculation of a confusion matrix. The results of classification were used for the AGB estimation.

2.3.2. Forest aboveground biomass estimation

AGB was estimated from local allometry (Shvidenko et al. 2008, Nikolaeva et al. 2008, Sevko 2014), where AGB is a function of the tree crown diameter for each species:

AGB = a*H+b (3)

for beech a = 7.8, b = -21.8 (r2=0.99), for cedar a = 13.1, b = -63.7 (r2=0.98);

H=a*CD+b (4)

for beech a = 3.9, b = 1.8 (r2=0.83), for cedar a = 4.5, b = 2.3 (r2=0.84);

where H – height of tree, CD – tree crown diameter. The average tree crown diameter algorithm was applied to derive crown diameter values from airborne hyperspectral data (Brovkina et al. 2015).

2.3.4. Assessment of solar radiation exergy

The exergy of the reflected solar radiation was calculated using the technique described by S. Yorgensen and Yu. Svirezhev using Landsat satellite data (Jorgensen & Svirezhev 2004) (5-7). This technique is based on multispectral images for a unit of surface which is performed by evaluating the "distance" between the real frequency distribution of the absorption spectrum of solar energy and the "equilibrium" frequency distribution. The degree of difference between the distributions is measured by the increment of Kullback entropy. The increment is zero when the frequency distribution of incoming radiation is equivalent to the frequency distribution of reflected radiation across the spectrum (meaning that the information receptor is equivalent to the information transmitter). If the Kullback entropy increment is positive, then there is an increment of information at the level of receptor and the reflective surface is in non-equilibrium state relative to the radiation spectrum.

$$E_x = E^{out}\left(K + \ln\frac{E^{out}}{E^{in}}\right) + B, \quad (5)$$

$$K = \sum_{v=1}^{n} p_v^{out} \ln\frac{p_v^{out}}{p_v^{int}}, \quad (6)$$

$$B = E^{int} - E^{out}, \quad (7)$$

where $E^{int} = \sum_{v=1}^{n} e_v^{int}$, incoming solar energy total; $E^{out} = \sum_{v=1}^{n} e_v^{out}$, reflected solar energy total; *n*-number of spectral bands; e_v^{int}, incoming energy in the range *v;* e_v^{out}, reflected energy in spectral range *v*; $p_v^{int} = \frac{e_v^{int}}{E^{int}}$, fraction of incoming energy in spectral range *v*; $p_v^{out} = \frac{e_v^{out}}{E^{out}}$, fraction of reflected energy in spectral range v. Spectral reflectance and surface temperature bands of satellite and airborne data will be inputs in (5 – 7).

2.3.5 Detection of forest decline

The algorithm to detect forest declination was based on Independent Component Analysis (Hyvarinen et al. 1997) that belongs to the methods for the detection of spectral anomalies and the automatic identification component of negative changes in the forest (Grigorieva 2014).

2.3.6 Validation of complex assessment of forest ecosystem

The official interior report "Dynamics of sanitary state of trees in the north part of the Baikalsky Nature Reserve" was used to validate the complex assessment of forest ecosystem from RS data.

3. RESULT AND DISCUSSION

Identification of tree decline from hyperspectral data (Fig. 3) successfully coincided with field reference data. An analysis of solar radiation exergy demonstrated significant variations of health and tree decline. These variations were interpreted as various exergy consumptions for the transpiration and the carbon deposition for trees of various healths. Results of complex modelling for assessment of the forest ecosystem in the Baikalsky Nature Reserve (Fig. 4) demonstrated that the average sustainability was 0.8 (medium to high level), and the anthropogenic load corresponded to 0.3 (medium level) in the study area (Table 2). Based on these indicators, the ecological situation was estimated as satisfactory. The forest ecosystem of the reserve has a margin of sustainability, but the degradation of conifers, the most sensitive to changes in the conditions of species' growth, indicates a decrease of the protective functions of ecosystems. The forest ecosystem state assessment from RS data corresponds to conclusions about the ecological situation in the official annual report of the Baikalsky Nature Reserve for 2015, where forest decline and drying of 10% of the cedar population was detected in the study area.

The usage of the proposed complex model allowed us to present a detailed map of the main forest-forming species and to identify forest stands with negative changes in health in the study area. This complex model for forest ecosystem state assessment seems promising for regional and large-scale forest monitoring and management.

Figure 3: Map of tree decline from hyperspectral data processing (red color represents tree decline)

Table 2. Indicators of ecological state

Indicator / year	2015
I, ecosystem's balance	0.4
R, degree of anthropogenic load	0.3
S, ecosystem sustainability	0.8
Assessment of ecological situation	satisfactory

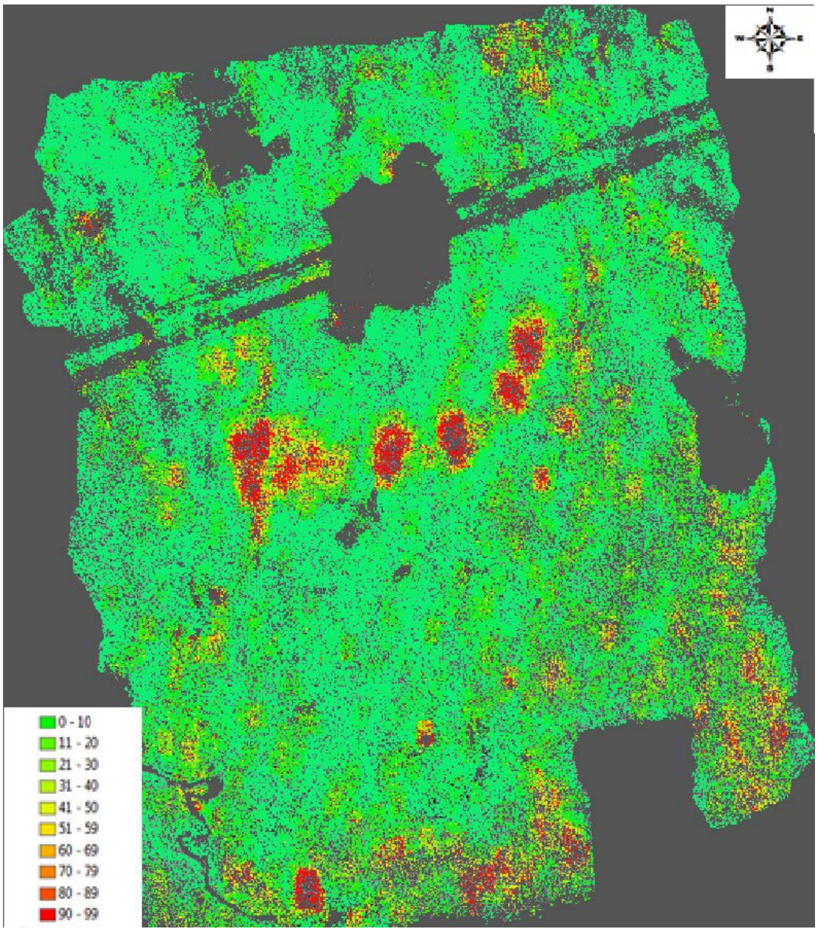

Figure 4: Map of ecosystem's balance (I) distribution on study area (I values are in %)

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