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REMOTE SENSING METHODS FOR PHYTOMASS ESTIMATION AND MAPPING OF TUNDRA VEGETATION

ABSTRACT

Mapping of above-ground phytomass provides a baseline for monitoring climate-induced changes, especially in the northern regions. This is important for practical applications, such as assessing quality of pastures and defining reindeer migration routes. Use of very high resolution (1 m and better) aerial and satellite images is of particular interest, because changes at the level of individual trees can be monitored over comparatively large areas. The goals of this study were to: i) establish relations between phytomass values and structure and spectral reflectance derived from ground research and ii) upscale from ground data to QuickBird satellite imagery to compile maps of above-ground phytomass for key sites. As a result, the study has produced a preliminary map of the above-ground phytomass of lichens for a test site in the Tuliok Valley, Khibiny Mountains, central Kola Peninsula, Russia, with phytomass values well in line with fieldwork data.

KEY WORDS: above-ground phytomass, lichens, Tuliok, Kola Peninsula, ground spectroradiometry, QuickBird, mapping

INTRODUCTION

Vegetation is the most informative component in studies of geosystems at different scales. Vegetation defines geosystem features and their structural and functional organization including processes of creation, transformation, and migrations of matter, energy, and information. Large-scale mapping of vegetation may be a useful tool in analysis of biodiversity and in monitoring of vegetation productivity. Cartographic methods facilitate identification of spatial patterns and structure; they also help to define the nature of vegetation changes and their trends, to determine vegetation productivity, and to develop cartographic models that describe situations arising from impacts of natural and anthropogenic factors. At the present stage, large-scale mapping and remote sensing data (RSD) enable the most accurate (depending on image resolution) representation of vegetation structure. Assessment of stocks and structure of above-ground phytomass is one of the primary challenges in addressing some of the problems of the rational use of natural resources, especially in less accessible northern areas. RSD can facilitate studies of

spatial structure of vegetation and of natural and anthropogenic factors that influence phytomass while minimizing labor-intensive fieldwork.

Biological productivity is a fundamental property of the biosphere. The term refers to the ability of living matter to reproduce biomass thus forming biotic cover. The issue of biological productivity in providing energy resources for ecosystem functioning is the object of studies of many researchers [Bazilevich, 1993; Ilyina, Yurkovska, 1999; Zlotin, R.I. 1995].

The main purpose of this study was to develop a methodology for mapping lichen phytomass of mountain and lowland tundra ecosystems using multi-spectral high-resolution satellite imagery in a case study on the Kola Peninsula.

OBJECTS AND METHODS OF THE RESEARCH

The study was conducted in two key plots that differed in topography and climate. The first site is located in the Tuliok River valley,

the Khibiny mountains, in the center of the Kola Peninsula. The second site with more severe climatic conditions is located on a low-hill plain near Lake Kanentiavr, east of Murmansk (Fig. 1).

The vegetation of Khibiny mountains is primarily of northern and sub-Arctic types and includes about 400 species of higher plants and lichens. Clearly marked altitudinal zonation is visibly expressed: the bottom of the valleys are occupied by spruce and pine forests and birch scrub woodlands; higher up in elevation, the landscapes change from forest-tundra to mountain tundra on the slopes of the mountains and to arctic deserts on the plateau-like tops. From 500–600 m in the Khibiny mountains, the upper and, occasionally, middle parts of the slopes, mountain tops, and glacial cirque bottoms are covered with mountain tundra phytocoenoses. The lower boundary of the tundra zone begins from a narrow strip of dwarf shrub tundra dominated by dwarf birch. The sites with a stable high moisture
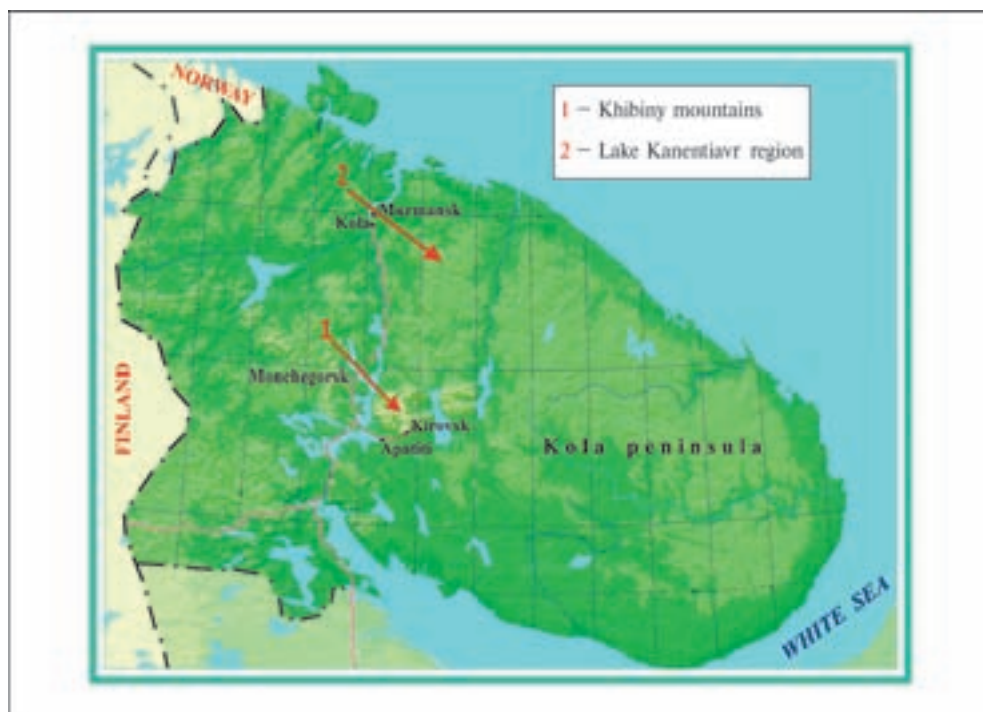

Fig. 1. Location of the sites.

regime and the steep slopes are associated with grass-dwarf shrub-green moss-dwarf birch tundra.

A significant part of the territory is occupied by dwarf shrub-lichen tundra. On the plateau-like tops of mountains, rocky dwarf shrub-lichen tundra is formed; here, the vegitation is the most sparse. Near Lake Kanentiavr, from north-east to south-west, fragments of tundra and forest tundra alternate successively. Forest-tundra is formed by birch primarily, whose patches grow together with tundra ecosystems. Along rivers, birch forests are developing. Tundra zone is heterogeneous and is represented in the north by dwarf shrub tundra dominated by crowberry (*Empetrum nigrum*), alpine bearberry (*Arctostaphylos alpina*), cowberry (*Vaccinium vitis idaea*), and dwarf birch (*Betula nana*); mosses and lichens cover up to 25% of the soil surface. Down south, dwarf shrub tundra is replaced by grass-shrub lichen tundra with crowberry, dwarf birch, blueberry *(Vaccinium myrtilis)*, alpine bearberry, alpine asalea *(Loiseleuria procumbens)*, and various species of lichens [Milkov, 1964; Ramenskaya,1983].

METHODS FOR MAPPING OF PRODUCTIVITY PROCESSES

There is a large variety of mapping techniques for representing productivity processes, among which are the two fundamental: the first method is based on field data and on previously created maps and the second method is associated with the use of RSD. Although today the second kind of mapping is considered to be the most widespread, especially for large and hard-accessible territories, field studies are needed for building "training samples" and for verification of models obtained.

Data on spatial and species structure of the plant cover were collected at the key plots. Samples were collected from the plots, 25 × 25 cm in size, to measure above-ground phytomass. Reflectance factors were identified using ground spectroradiometry.

These surface values were compared with the summer satellite imagery QuickBird 2005–2006 (spatial resolution of spectral bands is 2.4 m) for further compilation of maps of above-ground phytomass based on multispectral images. These activities continued the long-term studies that have been conducted in the central part of the Kola Peninsula beginning in 1993 [Ecology of the North, 2003; Kapitsa, Golubeva, 1997].

Indices are often used in work with satellite images. These indices represent parameters that combine reflectance factors of image pixels in several spectral bands. Such derived features are most widely used in analyses of vegetation cover [Labutina, 2004]. These features include characteristic differences in spectral reflectance of plant objects in the red and near infrared bands of the electromagnetic spectrum. Differences in the optical characteristics of plants in these bands are associated with the composition and state of plant pigments and tissues, morphology of plants in general, age, and different environmental conditions. Vegetation pigments absorb light energy selectively, most intensely in the red spectrum, while the near infrared region is associated with the maximal reflectance of vegetation. There are several versions of vegetation indices, including the VI (Vegetation Index), the SAVI (Soil Adjusted Vegetation Index), the NDVI (Normalized Difference Vegetation Index), as well as dozens of other indices, some of which represent modified indices mentioned above while others are more complex indices based on biophysical modeling and calibration with ground-based data, such, for example, as the LAI (Leaf Area Index) [Labutina, 2004]. The NDVI, which is a simple quantitative index of green biomass, is most often used when interpreting the vegetation cover. The NDVI is calculated as follows:

$$\mathbf{NDVI} = (\mathbf{V}ir - \mathbf{V}r)/(\mathbf{V}ir + \mathbf{V}r),$$

where **V**r and **V**ir – reflectance in the red and infrared bands of the spectrum, respectively. The calculation of the NDVI is based on the

two most stable (not dependent on other factors) parts of the spectral reflectivity curve of vascular plants [Knizhnikov, Kravtsova, Tutubalina, 2004].

Ground-based spectroradiometry mainly allows separation of vegetation by type, species composition, and its condition on the basis of spectral parameters, their correlation with phytomass, and through assessment of correspondence of ground and remote sensing data. Ground-based spectroradiometry allows separation of lichen, lichen-dwarf shrub, and dwarf shrub vegetation and separation of lichens by type. The shape of spectral reflectance clearly identifies dead plants and rocks with or without crustaceous lichens. It has been shown that specific levels of technogenic impact on tundra vegetation (i.e., completely dead tundra vegetation and vegetation with strong, medium, and slight damage) are expressed in four-channel ground spectroradiometry [Ecology of the North, 2003; Rees, Tutubalina, Golubeva, 2003].

Thus, ground spectroradiometry can be used to assist in understanding spectral representation of vegetation obtained using multispectral satellite images and for addressing various tasks: detailed measurements of spectral radiance/reflectance values, identification of dependences of spectral reflectance of objects upon various natural factors, and investigation of reflectance dependence upon the direction of observation under different lighting conditions.

During fieldwork, we gathered over fifty 25 × 25 cm vegetation samples, which were measured with a spectroradiometer and geobotanically described. The main goal of the field spectrometric studies was to determine the values of the reflectance coefficients for individual plant species and for specific areas that can be detected in high-resolution satellite images (Fig. 2). For this purpose, we used a portable field SkyeInstruments SpectroSense 2 + spectroradiometer (http://www.skyeinstruments.com), consisting of

two sensors, one of them pointing down and capturing reflected radiation within a solid angle of 25°, while the second sensor pointed up and covered by a diffusing glass capturing the incident and scattered solar radiation within the hemisphere. The measurements were made in four spectral bands, centered at the wavelengths of 475, 546, 677, and 837 nm. The results of the measurements were calculated to the coefficients of reflectance using calibration certificate of the device.

Measurement results were visualized as reflectance coefficient plots (Fig. 3), demonstrating the ability of green vegetation to selectively reflect incident solar radiation depending on species composition and conditions of plants.

After the measurement, all the above-ground vegetation was harvested from the key plots and separated by species and by green and non-green parts of plants. Later in the lab, the samples were dried at 105 °C and weighed to derive absolutely dry above-ground phytomass values.

The next stage was to define the relationship between the values of phytomass and two spectral metrics of samples derived from the ground radiometry: the NDVI and the average spectral reflectance in the visible spectrum (blue, green, and red spectral bands). For this analysis, absolutely dry phytomass values were summed up for three groups: green parts of plants, non-green parts of plants, and lichens. Then, linear regression analysis of these grouped phytomass values against the NDVI and against average visible reflectance was performed.

At the final stage, we have attempted to compile a preliminary map of the above-ground lichen tundra phytomass for the Tuliok site using the QuickBird image of 28.06.2006. We have identified lichen tundra areas on the preliminary classification map (courtesy of our colleague Anna Mikheeva) which was compiled by maximum likelihood classification of the QuickBird image.

We have calculated the NDVI image from the QuickBird image radiometrically corrected to radiance values. We have then used three GPS-located lichen tundra field plots within the Tuliok site to obtain the relationship between the ground NDVI and the satellite image-derived NDVI, by linear regression. Finally, we combined this relationship with
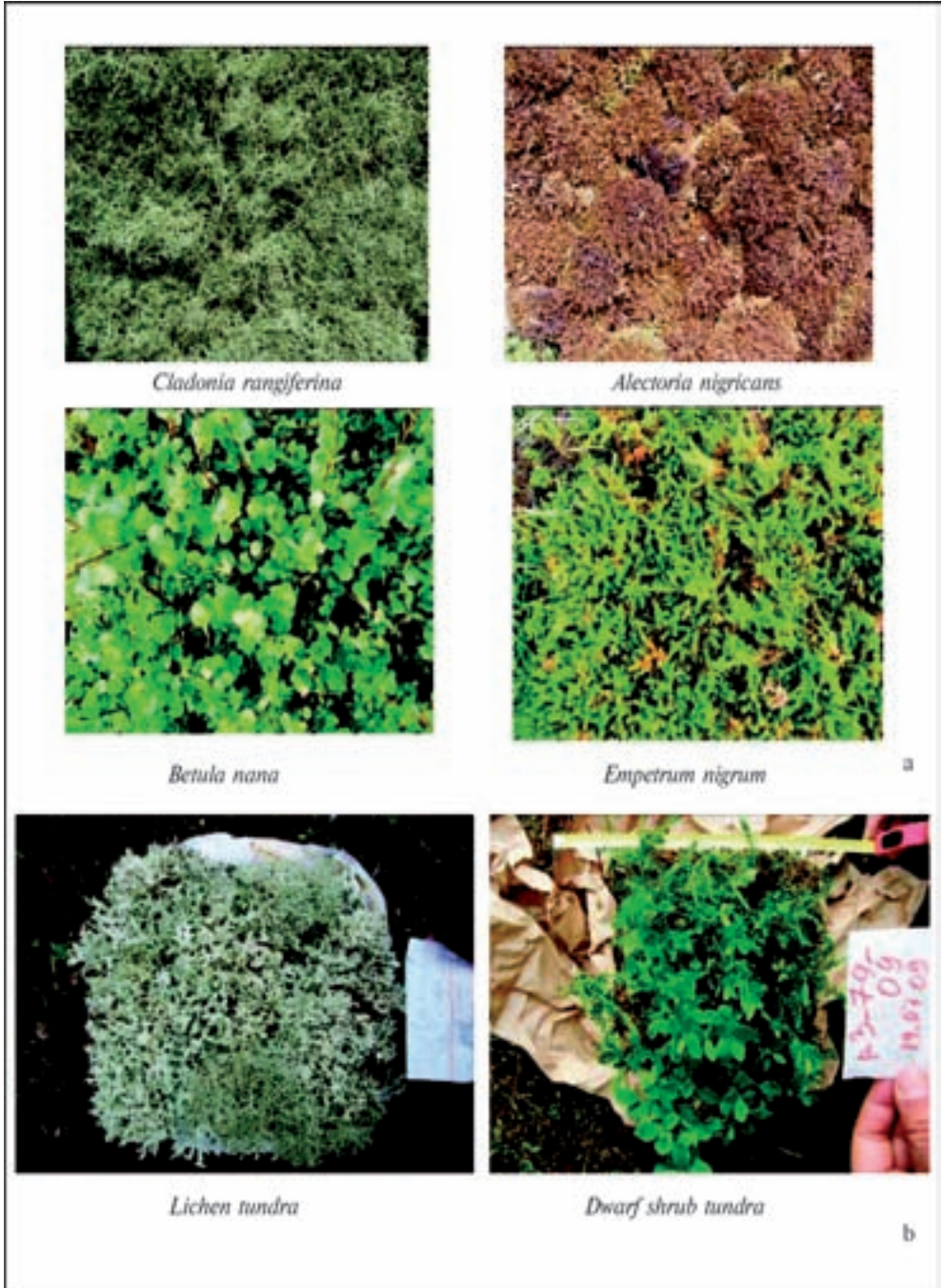

Fig. 2. Example of ground spectroradiometry samples: a) "pure" species, b) samples from test areas for comparison with satellite images
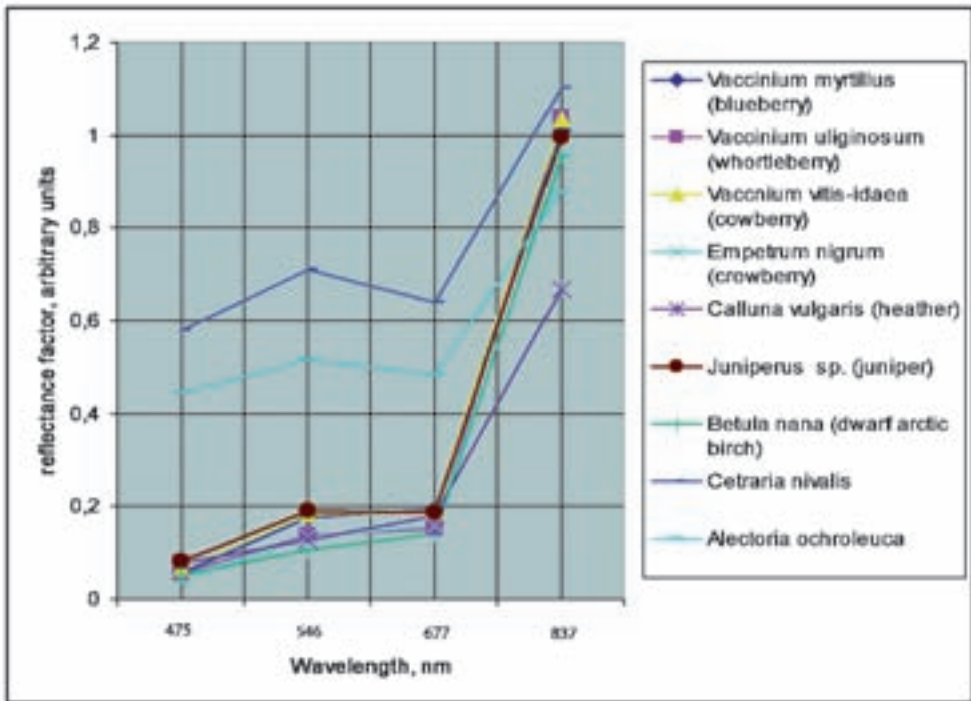
Fig. 3. Reflectance coefficients for typical tundra plant species.

the relationship between the above-ground phytomass of lichens and the ground NDVI established earlier to upscale from the ground-level to satellite data in order to create the map of the above-ground phytomass of lichen tundra within the limits of the "lichens" class in the QuickBird image classification.

RESULTS

Optical properties of forest-tundra and tundra landscapes of the Kola Peninsula were primarily determined by reflective properties characteristic of their moss, lichen, dwarf shrub, shrub, and tree components. Tundra landscapes have diverse optical properties. Most of light-colored, fruticose lichens (*Cetraria nivalis, Cladina mitis, Alectoria ochroleuca,* etc.) are characterized by high values of spectral reflectance in the measured bands (Rees et al., 2003). Experience gained in field interpretation of the Terra ASTER and the Landsat ETM+ images indicated that even small projective coverage of terrain

by lichens significantly increases the values of reflectance coefficients on the satellite images. In lichens, the maximum reflectance in the green band of the spectrum is weak; however, the transition to the infrared band is expressed relatively strongly. For almost all lichen species, the main region of the chlorophyll absorption in the red band is weakly expressed and it is in this spectral band that their reflectance coefficients are greater compared to higher plants.

The only high correlation values and significant relationships were found between the above-ground phytomass of lichen tundra with average reflectance (normal relationship, Fig 4b) and the NDVI (inverse relationship, Fig 4a). For all other vegetation groups, the correlations were very low and usually insignificant (Fig. 4 c, d e, f).

The derived relationship between the satellite-image (QuickBird) and the field (SkyeInstruments radiometer) NDVI values was as follows:
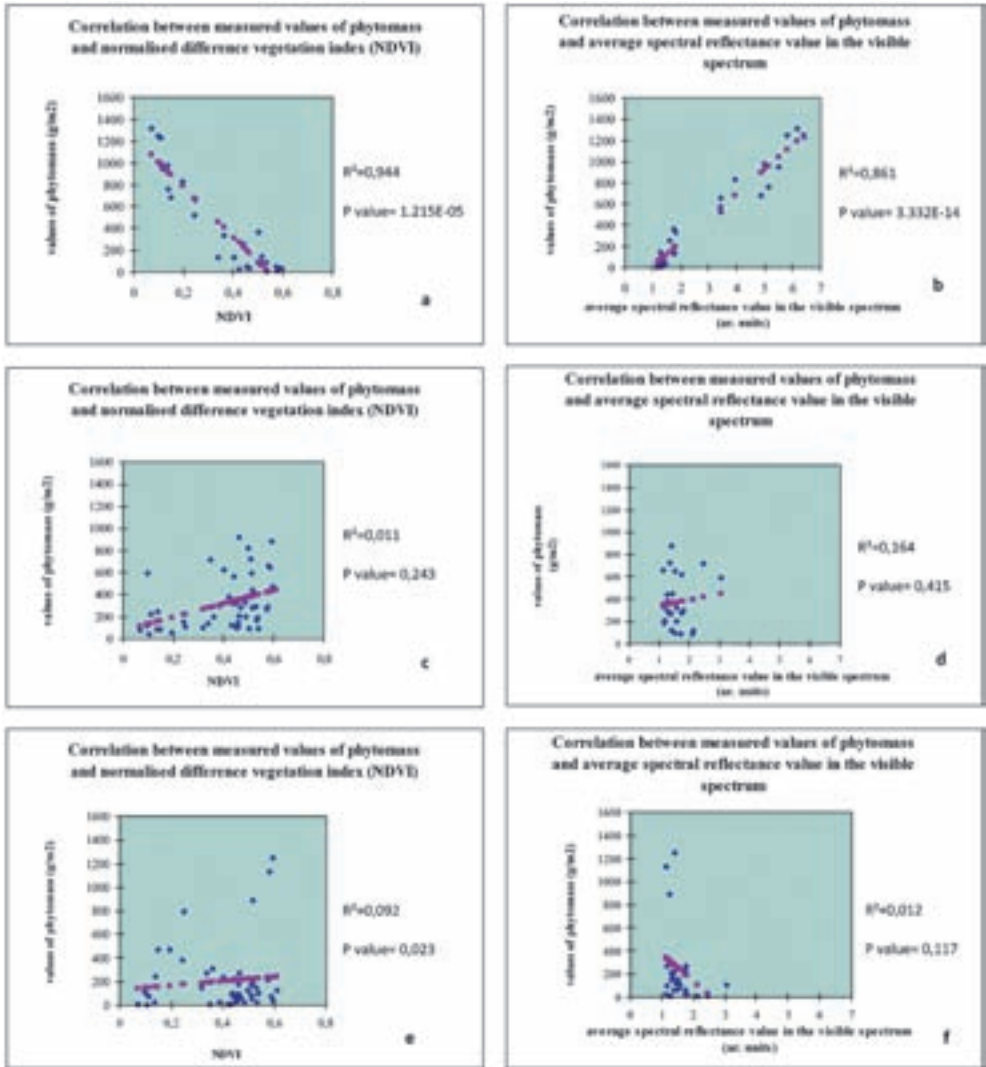
Fig. 4 Relationships between phytomass and spectral metrics of ground samples, where ◆ original values of photomass; ■ predicted values of photomass
(a, b – lichens; c, d – green part of phytomass; e, f – non-green part of phytomass)

$$\mathbf{NDVI}_{field} = \mathbf{NDVI}_{sat.im} \cdot \mathbf{0.542 + 0.031.}$$

This relationship was obtained by linear regression using three field samples of lichen tundra only (more samples were not available for the Tuliok area). The relationship is characterized by a low R^2 (0.247), and a high P-value (0.876). However, the compiled preliminary map of the above-ground phytomass of lichen tundra (Fig. 5) displays a plausible range of phytomass values (from over 860 to just below 1,100 g/m^2) which is in good correspondence with the field data on above-ground phytomass (for the Tuliok field sites with the most pure and thick lichen cover, it varied within 940–1,230 g/m^2).

CONCLUSION

We have successfully demonstrated the potential for deriving the above-ground tundra phytomass maps from very-high resolution satellite imagery. Definite relationships between spectral and phytomass characteristics were derived only for lichen tundra. This is probably because
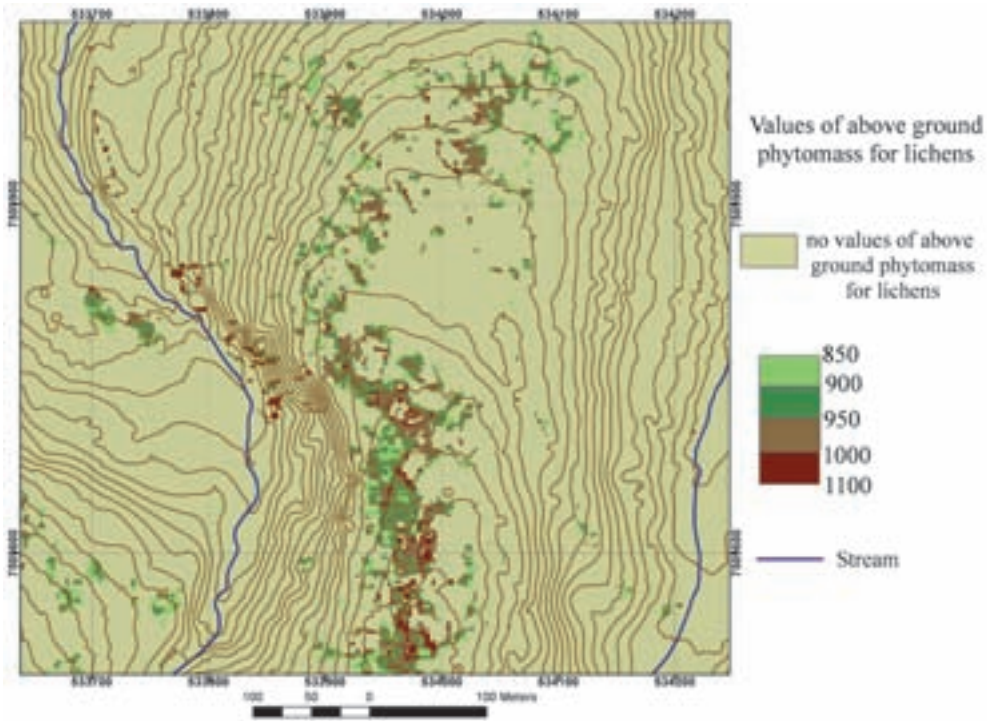
Fig. 5. Map of above-ground phytomass of lichen tundra at the Tuliok site.

the lichen tundra samples are much more homogenous vertically and do not have many vertical levels in comparison with the samples dominated by green vascular plants; this is of a great importance because ground and satellite radiometers predominantly measure radiance from the top surfaces of samples. Also, lichen tundra has a lesser variety of species and a lesser spectral diversity. It is important to note that the spectral properties were measured when samples were in their natural moist condition; however, we were not able to weigh moist phytomass in situ.

There were many uncertainties in subsequent upscaling from the ground data to the satellite image-derived map of the lichen tundra phytomass. First, the boundaries of lichen areas need field validation (in some areas at Tuliok, lichens and light stones are spectrally similar). The upscaling from the field to the satellite NDVI was not very accurate due to a small statistical sample size, spatial resolution effects (the NDVI of the field 25 × 25 cm

samples was upscaled to the satellite image NDVI of 2.4 × 2.4 m pixels), and GPS location uncertainties (accurate only to several meters). However, the resulting map shows a plausible range of the phytomass values and conservative estimates suggest that the error in the phytomass estimation is well below 50%.

REFERENCES:

1. Bazilevich, N.I. (1993). The biological productivity of ecosystems of northern Eurasia, Moscow: Nauka. 394 p. (in Russian).

2. Ecology of the North: remote sensing study of terrestrial ecosystems. (2003). Ed. A.P. Kapitsa and W. G. Rees. Moscow: Nauchnyi Mir. 248 p. (in Russian).

3. Ilyina, I.S. and Yurkovska, T.K. (1999). Phytoecological mapping and its current problems // Botan. Journ. 1999. Vol. 84, № 12. pp. 1–7.

4. Kapitsa, A.P., Golubeva, E.I. (1997). The structure of tundra plant cover as an ecological indicator in the Kola Peninsula // R.M.M. Crawford (ed.). Disturbance and Recovery in Arctic Lands. Printed in the Netherlands. NATO ASI Series. 1997 Kluwer Publishers. pp. 283–291.

5. Knizhnikov, Yu.F., Kravtsova, V.I., Tutubalina, O.V. (2004). Aerospace methods of geographical research, Moscow: Academia. 336 p. (in Russian).

6. Labutina, I.A. (2004). Interpretation of space images, Moscow: Aspekt-Press. 184 p. (in Russian).

7. Milkov, F.N. (1964). Natural areas of the USSR. – Moscow: Publishing House Mysl. 326 p. (in Russian).

8. Ramenskaya, M.L. (1983). Analysis of the flora of the Murmansk region and Karelia / M.L. Ramenskaya. – Leningrad: Nauka. 216 p. (in Russian).

9. Rees, W.G., Tutubalina, O.V., Golubeva, E.I. (2003). Reflectance spectra of subarctic lichens between 400 and 2400 nm. Remote Sensing of Environment. 2003. Vol. 90, Issue 3, pp. 281–292. doi:10.1016/j.rse.2003.12.009.

10. Zlotin, R.I. (1995). Organization of ecosystems. Moscow: Mysl. 240 p. (in Russian).

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