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AEROSPACE MAPPING OF THE STATUS AND POSITION OF NORTHERN FOREST LIMIT

ABSTRACT. We study changes in the position of the northern forest limit and state of vegetation in the taiga-tundra ecotone through aerial and satellite imagery in the context of climate variability and of the projected advance of forests to the north. Our research of reference sites in Kola Peninsula and in Central Siberia has been part of PPS Arctic project of the International Polar Year. Studying the dynamics of ecotones by remote sensing is difficult due to poor display of ecotone vegetation in satellite images, and this required a range of techniques, regionally adapted and based on remotely sensed data of different spatial resolution. We characterize the newly developed techniques that enabled to identify vegetation change in recent decades: advance of forest up the slopes by 30 m in the Khibiny Mountains; advance of lichen-dwarf shrub tundra into lichen tundra in the north of Kola Peninsula; increasing stand density in sparse larch forests in the Khatanga River basin in the Taimyr Peninsula.

KEY WORDS: taiga-tundra ecotone, dynamics of the forest limit, satellite images

INTRODUCTION

The dynamics of the northern limit of forests (and of their upper limit in the mountains) have attracted attention in the context of climate change. The global air temperature increase is most noticeable in the polar regions [Henning, 2007]. The prospective displacement of the northern tree line is considered as one of the possible consequences of global warming [Kislov et al., 2008].

Existing models of the dynamics of the forest line in the next century are not yet accurate enough because of the lack of reliable data about its current position, and due to the poorly studied influence of different factors. Aerospace remote sensing provides an opportunity to accurately map the current structure of the taiga-tundra transition zone, as well as the dynamics of the northern forest line over the past decades. In Russia, solving this problem is timely for the inventory of natural resources, assessment of trends in forest resources due to climate, and to assess changes in forest distribution for determining the carbon balance, which has both research and policy significance in light of the Kyoto Protocol. Poorly defined boundaries of the northern forests, both on the ground and as depicted in the aerospace images, create difficulties in defining both the boundaries and their changes, and, in most cases, this transforms the problem to assessing the state of the transition *zone* between the tundra and taiga (taiga-tundra ecotone), and changes in the zone structure.

However, an appeal to the remote sensing methods inevitably encounters the problem of "scope-resolution": weakly expressed differences in the transition zone require the imagery of the highest possible detail, which is possible only for a local level, and circumpolar nature of the phenomenon requires a transition to a global level, and more general images, characterized by low detail. New image processing techniques are needed to overcome these contradictions.

THE PPS ARCTIC PROJECT RESEARCH APPROACH

The remote sensing research presented here has been carried chiefly by researchers of the Laboratory of Aerospace Methods of the Department of Cartography and Geoinformatics, Faculty of Geography, M.V. Lomonosov, participating in research of the taiga-tundra ecotone within the framework of the PPS Arctic project ("Present day processes, Past changes, and Spatiotemporal variability of biotic, abiotic and socio-environmental conditions and resource components along and across the Arctic delimitation zone") of the Circumpolar International Polar Year (IPY, 2007–2010), and of complementing Russian-Norwegian project BENEFITS ("Natural and Social Science Research Cooperation in Northern Russia and Norway for Mutual Benefits across National and Scientific Borders)". The PPS Arctic scientific consortium includes more than 150 researchers and students from Norway, Canada, Russia, the UK and other countries, and has been jointly managed from Norway and the UK (see http://ppsarctic.nina.no/); the BENEFITS project has been coordinated by Dr Annika Hofgaard of Norwegian Institute for Nature Research.

In 2008, common protocols have been developed for collecting and processing field data (PPS Arctic Manual), focussing the studies on three ecotone boundaries: forest line, treeline and krummholz line. Field studies were planned for a set of reference sites in the lowland and mountain areas, selected in such a way as to investigate the influence of marine-continental and north-south gradients, as well as the ecotones of Western and Eastern hemispheres as a whole (Fig. 1). Common criteria were used for the forest line: trees in the forest must have a minimum height of 3 m, the distance between the trees should not exceed 30 m. Single standing trees must be at least 2 meters, otherwise they are not considered as trees.

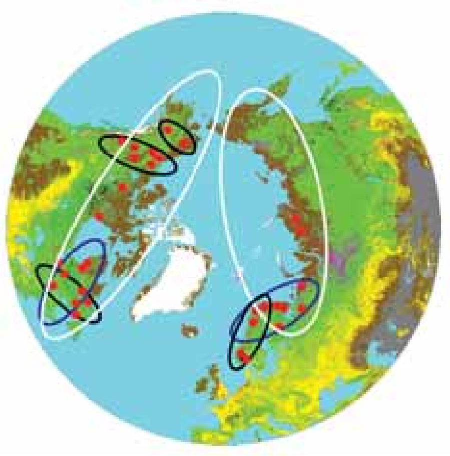


Fig. 1. Reference sites of field research for the PPS Arctic project (shown in red). Black ellipses show the studied north-south gradients, blue ellipses – regional west-east gradients, and white ellipses show continental west-east gradients

The Russian part of the project includes studies of the dynamics of the northern forest line on the basis of ground and remotely sensed data for reference sites on the plains and in mountainous areas in the European and Asian parts of Russia [Rees et al, 2009]. Field research for this project, involving 20 students and graduate students of Faculty of Geography of Moscow State University, has been conducted in 2008–2010 by an international expedition to the Kola Peninsula (Khibiny and the hilly lowland area near Lake Kanentiavr), and in 2010 in Central Siberia, on the Taimyr Peninsula and at the slopes of Putorana Plateau. The work focused on complex geobotanical profiles covering the transition from forest to tundra (Fig. 2), and test plots, located along the profiles. Spatial and age structure of stands, their density, annual growth, species diversity

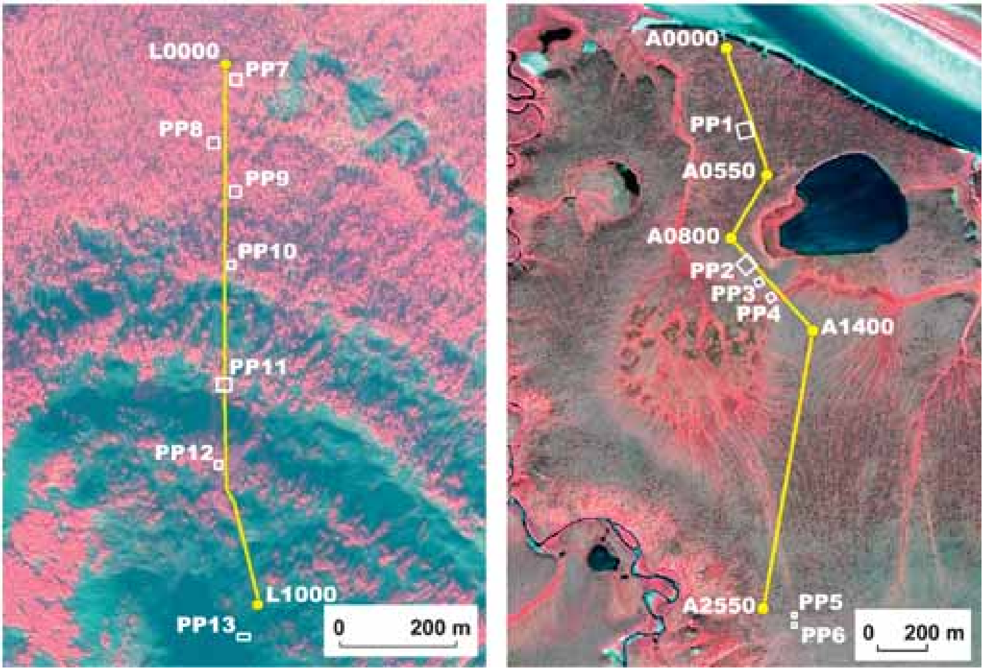


Fig. 2. Profiles (transects) of field research for the PPS Arctic project at Omon Yuryakh, Putorana plateau (left) and Ary-Mas, Taimyr (right). Numbers in point names on the transect signify distance from the start of the transect in meters. Squares show test plots near transects that were used for detailed morphometric and dendrochronological research

have been assessed, soil and permafrost were studied, ground 4-band spectroradiometry of plants and field interpretation of very high resolution (sub-meter) satellite images have been carried out.

Interim results have been discussed at the annual workshops in Cambridge (UK), Edmonton (Canada), Tromso (Norway), Apatity and Zvenigorod (Russia), and at the final BENEFITS meeting in Moscow (Russia) in 2011. Research of young scientists has been well represented at the Oslo IPY Conference in 2010, and at a conference on global climate processes and their effects on the ecosystem of the arctic and subarctic regions in Murmansk in 2011. Results presenting the dependence of phytomass values of lichens on their spectral characteristics have been published [Golubeva et al., 2010], while another study combining age structure analysis with remote sensing studies to estimate mountain treeline dynamics in Khibiny is nearing publication [Mathisen et al., in review, preliminary findings published in Mikheeva et al., 2010]. The current paper presents the development of original remote sensing methods for studies of vegetations structure and its dynamics in the taiga-tundra ecotone, which in Russian studies is called the forest-tundra zone.

FEATURES OF THE FOREST-TUNDRA ZONE AND THEIR PORTRAYAL IN THE PUBLISHED MAPS

Forest-tundra zone is bordering the northern face of Russia, stretching over a distance of some 6000 km. Russian landscape maps and maps of vegetation convey different views on the forest-tundra zone held by landscape scientists and biogeographers: it is shown as a part of the subarctic zone groups (map of landscapes in the National Atlas of Russia [Natsionalny..., 2007]; landscape map of the USSR for higher education institutions, ed. A.G. Isachenko [Landshaftnaya..., 1988]), as well as a subzone in the taiga zone (map "Vegetation zones and types of altitudinal zonality for Russia and adjacent territories", ed. G.N. Ogureeva [Zony..., 1999]). The map of vegetation of the USSR for higher education institutions [Karta..., 1990] and map of vegetation in the National Atlas of Russia [Natsionalny..., 2007] show pre-tundra sparse forests at the northern boundaries of the forest vegetation. Comparison of contours of these differently interprereted landscape and vegetation units shows that it is the same transition zone.

Forest-tundra zone extends, with a few interruptions (punctuated mainly by corridors of large river valleys) along the southern boundary of the tundra and the northern boundary of the forest, and has a width of 40 to 300 km. The structure and species composition of vegetation in this zone demonstrate considerable spatial diversity from west to east, as determined by the diversity of ecotone landscape conditions. On the map of vegetation in the National Atlas of Russia [the National..., 2007] six types of pre-tundra sparse forests on plains are identified (the Atlantic sparse birch forests of the Kola North; birch and spruce sparse forests of northern European Russia; pre-Urals spruce and larch sparse forests; fragmented larch, spruce, pine and birch forests of Western Siberia; larch-spruce sparse and very sparse forests of Central Siberia; larch sparse and very sparse forests of Eastern Siberia).

The width of the pre-tundra forest zone varies from 40–60 km in the Kola Peninsula to 120 km in the middle part of the European north and 40–80 km in the Urals. Fragmented forests of Western Siberia are spread in the zone of 80–160 km wide, expanding in the valley of the Yenisei to 250 km. A continuous strip of sparse forests near the Khantaiskiy trough is 80–150 km, in the Anabar-Lena area it is 80 km wide, then it is interrupted by the Yana-Indigirka lowlands, where the lowland tundra contact directly with the altitudinal taiga belt Verkhoyanskiy and Cherskiy ridges. This band is once again extended to 350 km width on the Kolyma lowland and merges with the larch woodlands of the mountains of the North-East, which are transitional to mountain tundra. In the Far East, small fragments of lowland pre-tundra sparse forests are changed by mountain sparse forests and tundra-to-sparse forests altitudinal zone spectra, with participation of *Pinus pumila* krummholz.

THE SPECTRUM OF METHODOLOGICAL APPROACHES

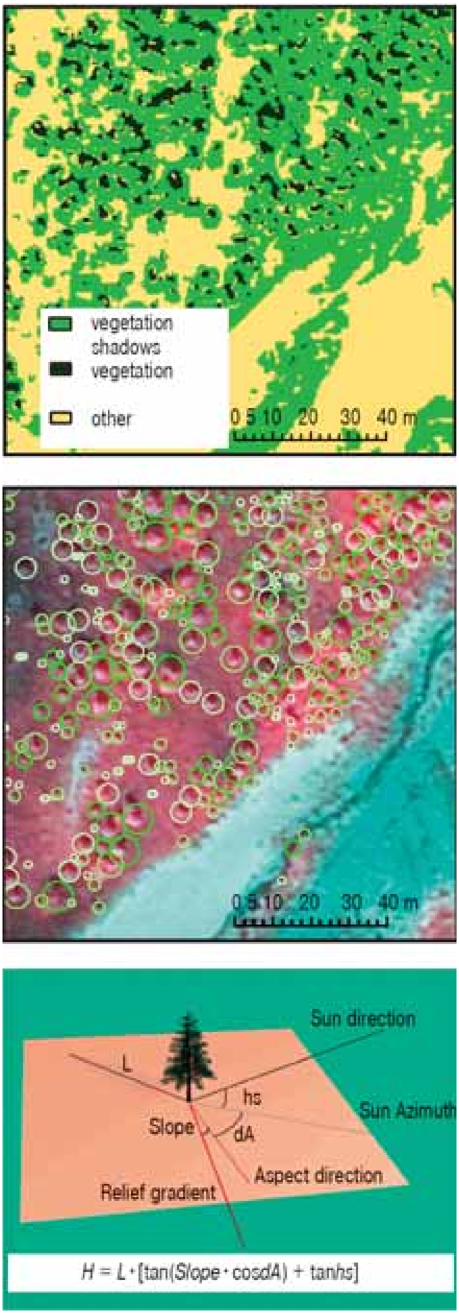
Each of these listed regions has its own characteristic vegetation of the forest-tundra zone. Availability of remotely-sensed imagery of required resolution and repeatability, along with the regional variability, determine the different methodological approaches to the use of aerospace imagery to study the dynamics of the northern forest line and the tundra-taiga ecotone. This is particularly evident in our research in two very different regions – in the Kola Peninsula and Taimyr Peninsula, where the Laboratory of Aerospace Methods has developed a whole range of methodological approaches, as described below. In development of these methods both the authors of this article, and their students took part. These include undergraduates, Master and Ph. D. students of the Department of Cartography and Geoinformatics: A.R. Loshkareva, A.I. Mikheeva, A.E. Novichikhin, A.Yu. Tyukavina.

With differences of landscape conditions and species composition, each of these two study areas has its own features of the transition from taiga to tundra. The Kola North birch scrub, containing crooked and stunted, but still fairly dense tree stands (crown coverage 0,2) grows in separate "islands", and then in groups of trees within tundra vegetation, which represents a complex alternation of rocky patches, lichen, and dwarf shrub tundra. In Central and Eastern Siberia, where the northern forest limit is formed by sparse larch forests, their canopy closure towards the North reduces even further, and they transform into very sparse forests with canopy cover of 0,1 [Ary-mas, 1978], and then only single stunted trees remain among the even cover of dwarf shrub tundra. In mountainous areas, the spatial structure of vegetation in the transition zone, is strongly influenced by the nature of the tree stand and by topographic features.

In our studies on the Kola Peninsula (Khibiny mountains and hilly lowlands near the Lake Kanentiavr) and on/just south of the Taimyr Peninsula (in the lowland area at the Ary-Mas site, and in the mountainous region of Putorana plateau) we have developed original techniques of visual and automatic interpretation of northern forests using the modern very high (sub-meter) resolution satellite imagery, which in this article we further call VHR images. It has been for the first time that Russian geographers had a number of such images for this task, providing a detailed study of the current state of ecotone, its boundaries and structure.

DELINEATION OF THE NORTHERN FOREST LIMIT AND RESEARCH OF THE CONTEMPORARY STRUCTURE OF THE TAIGA–TUNDRA ECOTONE USING THE VERY HIGH RESOLUTION IMAGERY

The gradual transition from taiga to tundra required the use of VHR satellite images, which appeared only in the 2000s. In our project studies, along with more traditional Landsat TM and ETM + (resolution 30 m), and Terra ASTER (15 m) imagery, Ikonos (0,8 m), QuickBird (0,6 m), GeoEye (0,4 m), and WorldView-1 and 2 (0,4 m) images were used. The analysis of VHR images for tundra-taiga ecotones in the Kola Peninsula, Taimyr and Sakha regions identified that WorldView-2 and QuickBird had the best quality for interpretation of single trees [Novichikhin, Tutubalina, 2010, Novichikhin, 2011]. An enhanced technique for the automatic deleineation of single trees and tree stands has been developed, called shadow-vegetation technique [Novichikhin, Tutubalina, 2009]. This technique is an algorithm for processing VHR satellite images jointly with a digital terrain model to determine the spatial position of trees (using the brightness contrast between illuminated tree tops and tree shadows) and calculate heights of trees from their shadow lengths (Fig. 3).



$$H = L \cdot [\tan(Slope \cdot \cos dA) + \tan hs]$$

Fig. 3. The shadow-vegetation method of automated tree stand interpretation: location of tree position using crown/shadow brightness contrast and derivation of tree height from its shadow length [Novichikhin, Tutubalina, 2009]:

a – pre-processed satellite image,
b – result of automated tree crown location,
c – principle of deriving the tree height (H) from the tree shadow length with account of Sun position, slope angle and aspect

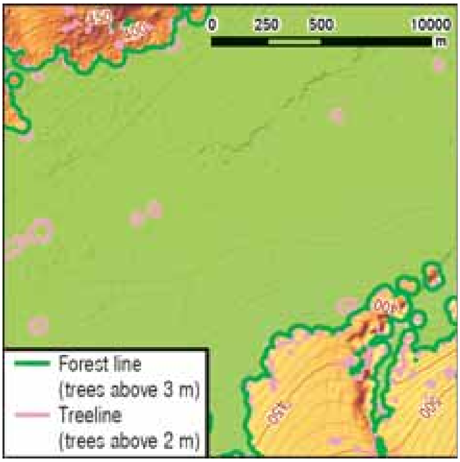


Fig. 4. Results of automated delineation of ecotone boundaries controlled b tree stand parameters in Tuliok River valley, Khibiny mountains [Novichikhin, Tutubalina, 2010]

The method also includes the creation of derivative maps of the spatial structure of forest stands – their canopy closure and stand density, and the canopy height. It also provides for delineation of forest and forest-tundra boundaries using the parameters of the forest stands (tree height and the distance between trees), which was especially important in the international project. On the basis of this method, key ecotone boundaries in a reference area of the Tuliok River valley in the Khibiny mountains were mapped in an automated way. These are forest line (delineating the boundary of forest areas where trees are at least 3 m tall and not more than 30 m apart), and tree line (delineating the extent of areas with trees at least 2 m tall and more than 30 m apart) (Fig. 4).

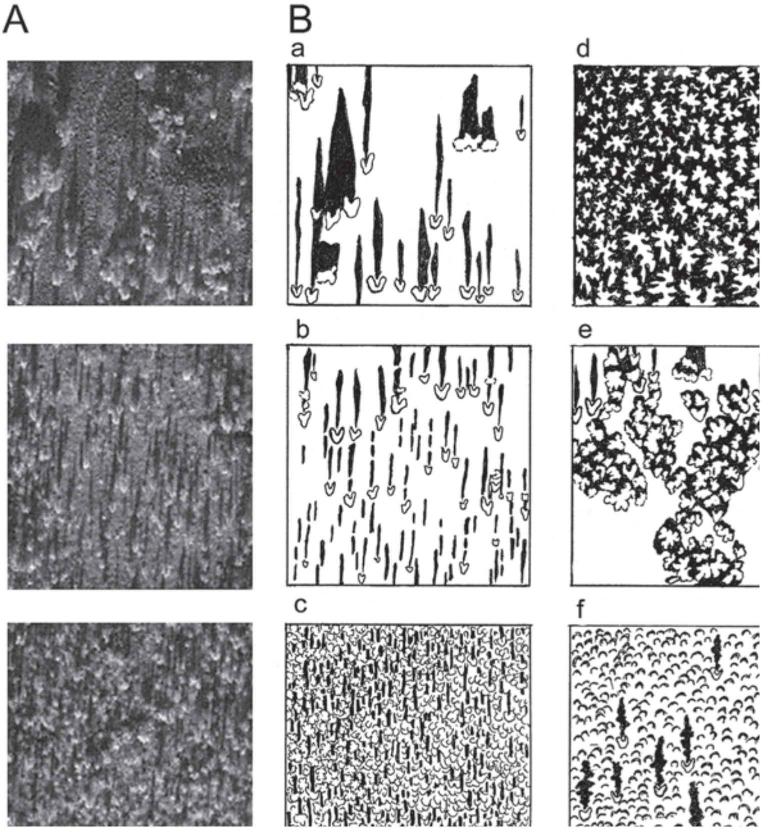


Fig. 5. Subsets of GeoEye satellite image showing various forest types in Putorana plateau (A) and graphic representation of satellite image structure (B).

a-f are explained in the text

Automated interpretation of plant communities a QuickBird satellite image on the basis of a specially performed ground spectroradiometry experiment (which is characterised further below) allowed to map the current state of vegetation in the taiga-tundra ecotone in the Tuliok River valley area, showing the quantitative proportion of components of the ecotone (woody vegetation, shrubs, lichens, rocky surfaces), which provides framework for long-term monitoring of the dynamics of the ecotone [Mikheeva, 2011b].

VHR images are not only good for automated processing, but provide rich material for visual interpretation of northern forests and the transition zone, describing in detail the spatial structure of vegetation. It has been well manifested in the Putorana plateau area, where the spatial features of the sparse forest image are defined by the shadow component which depends on tree species. Figure 5 presents satellite image subsets (A) and graphic representations (B) of the major plant communities of the reference site on a slope in the basin of Omon-Yuryakh River in Putorana plateau: larch very sparse (a) and sparse forests (b), larch forests with birch and alder (c), alder scrub (d), patches and areas of alder scrub with single larch trees (e, f).

Since both visual and automated interpretation requires modern VHR images, it holds potential for extending the research of ecotone dynamics into the future, but does not provide for retrospective dynamics analysis in the preceding period, characterized by warming. The retrospective analysis requires additional data from the second half of 20th century.

METHODOLOGICAL APPROACHES TO RESEARCH OF THE DYNAMICS OF THE NORTHERN FOREST LIMIT AND THEIR RESULTS

In the PPS Arctic project, our group tried a number of methodological approaches to identify the dynamics of the northern forest limit and changes in vegetation structure at the taiga-tundra transition.

Comparison of multitemporal topographic maps

In studies of the dynamics of various natural objects it is natural to turn to current and past topographic maps. For the reference site in hilly lowlands near Lake Kanentiavr in northern Kola Peninsula, we attempted to use topographic maps of 1960 (scale 1:50 000) and 1980 (1:25 000). To detect changes in the distribution of forests in this period which was characterized by slight warming, according to Murmansk meteorological station data. The gradual transition from forest to tundra in the area entails vagueness of the tree line in topographic maps. Small patches of sparse forest and stunted trees are represented by point symbols on the maps, rather than delineated by areas; as a result area comparisons from one date to another become impossible. In addition, the criteria for the separation of forest and undergrowth by stand height on Russian topographic maps are not entirely consistent with these in the PPS Arctic project (which considers as forest stands more than 3 m in height, with distances between trees not more than 30 m). Therefore, our attempt to use topographic maps for the analysis of ecotone dynamics failed: the identified small changes of forest cover, when checked against historical aerial images, proved to be errors of map compilation [Kravtsova, Loshkareva, 2009].

Comparison of multitemporal sub-meter resolution images: aerial photos of 1950s–1960s and contemporary VHR satellite images

This method has been used successfully to detect changes. By employing aerial photographs of the 1950s, which were compared with the modern high-resolution satellite imagery QuickBird, advance of pine and birch treeline up the slopes by 30 m was identified in Khibiny mountains in 1958–2008. It is important that acceptable accuracy in defining the change of this boundary has been achieved only by creating and using an

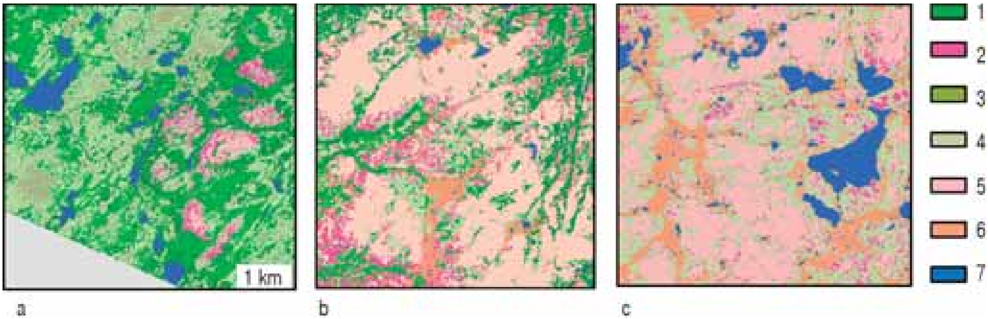


Fig. 6. Changes in vegetation in the north of Kola Peninsula in 1986-2006 as identified by comparing multi-temporal aerial photographs and Terra ASTER images:

a – in birch scrub at the northern boundary of the forest zone; b – in lichen-dwarf shrub tundra, with groups of trees and individual trees in the forest-tundra zone; c – in dwarf shrub-lichen tundra [Kravtsova, Loshkareva, 2009]. Changes: 1 – birch scrub forest in place of forest-tundra (site a) and thickening of the shrub and dwarf shrub vegetation in the tundra (site b); 2 – forest-tundra replacing the lichen tundra. No changes: 3 – birch scrub, 4 – forest-tundra, 5 – dwarf shrub-lichen tundra, 6– wetlands, 7 – lakes

accurate digital elevation model, in this case from GeoEye-1 stereo imagery [Mikheeva, 2011a].

In the lowland northern Kola Peninsula changes of the state the taiga-tundra ecotone in the period of climate warming have been studied in local areas by comparing aerial photographs of 1986 with ASTER satellite images of 2006 (resolution 15 m) [Kravtsova, Loshkareva, 2009]. The study region in the vicinity of Lake Kanentiavr offers a good selection of areas of transition between taiga and tundra: the northern (in this case north-eastern) edge of the forest zone represented by birch scrub; forest-tundra transition zone, which is a combination of dwarf shrub tundra with small patches of birch scrub, groups of birch trees and individual birches; and southern edge of the tundra zone, represented by dwarf shrub-lichen tundra without trees. Maps of changes in vegetation were compiled for reference sites in forest, forest-tundra and tundra zones (Fig. 6). They demonstrated that in the forest zone stand density has been increasing, without change in the boundaries of forests. In the forest-tundra zone a marked thickening of the dwarf shrub vegetation occurred, resulting in advance of the lichen-dwarf shrub tundra into dwarf shrub-lichen tundra. Within the lichen tundra, changes were not detected.

However, the limited coverage of high-resolution images and the time-consuming visual processing make this successful method applicable only locally, rather than for large areas.

Transition from sub-meter to 30-meter satellite image interpretation

Turning to the aerospace images to identify the dynamics of northern vegetation in the context of climate variations, it is necessary to have images over recent decades (covering the period of warming), made with the same type of the imaging system. Images from Landsat satellites are most compatible with this requirement. However, as identified in our experiments, their resolution (30 m) is not sufficient to accurately locate the limits of northern forests. A careful analysis performed for lowland northern Kola Peninsula, using high-resolution imagery from the QuickBird satellite (0,6 m), demonstrated that the Landsat images show boundaries between different types of forests (birch forests with herbaceous and shrub understorey), but the boundary between forest and dwarf shrub tundra is not visible [Kravtsova, Loshkareva, 2010] (Fig. 7), while precisely this invisible boundary represents the northern limits of forest in this part of the Kola Peninsula.

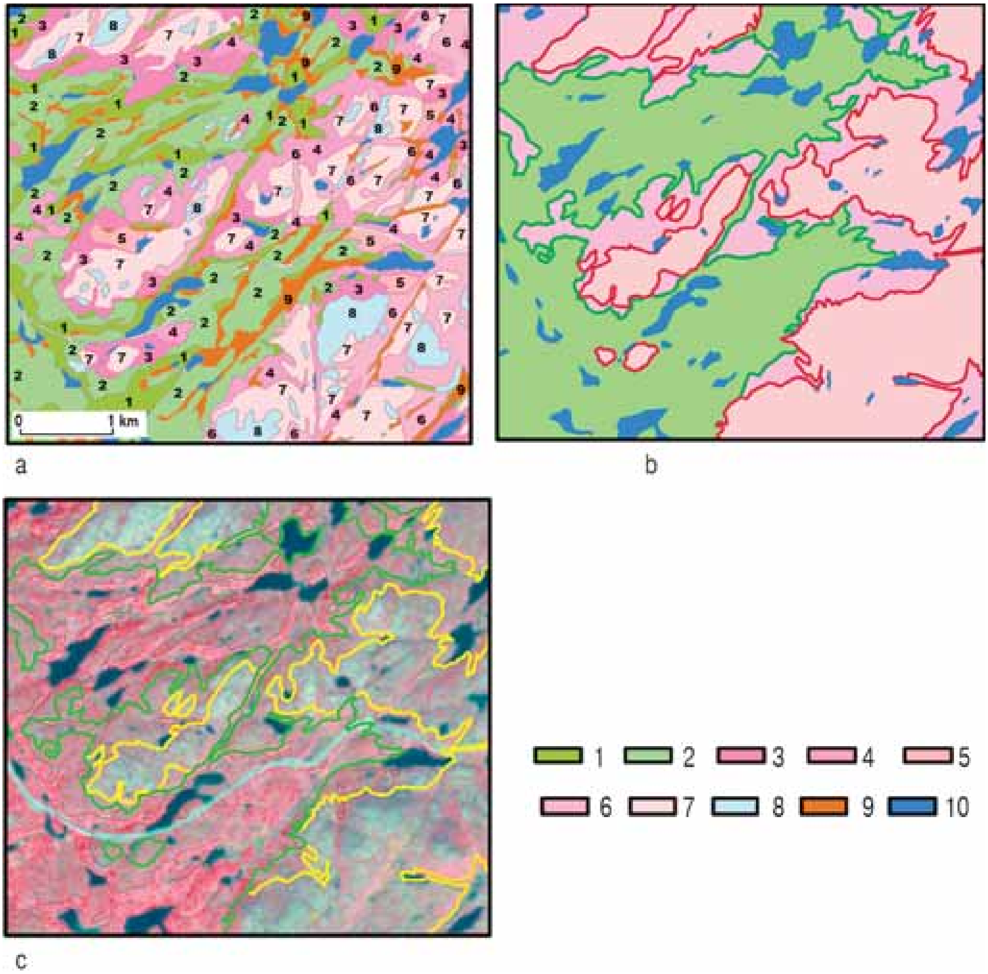


Fig. 7. Visual interpretation map of the QuickBird satellite image (A), identified forest and forest-tundra boundaries (B) and overlay of these boundaries onto a Landsat TM satellite image (C) [Kravtsova, Loshkareva, 2010b]. Ecosystems on the visual interpretation map A:

I. Forests: 1 – grassy birch forest, 2 – birch forest with dwarf shrubs.

II. Forest-tundra: 3 – lichen-dwarf shrub tundra, with groups of trees, 4 – lichen-dwarf shrub tundra, with individual trees, 5 – dwarf shrub-lichen tundra with individual trees.

III. Tundra: 6 – lichen- dwarf shrub tundra, 7 – dwarf shrub-lichen tundra, 8 – rocky lichen tundra.

IV. Intrazonal ecosystems: 9 - wetlands, 10 - lakes. Boundaries: green - the upper (northern) forest line; pink (on map B) and yellow (map C) - the upper (northern) treeline (individual trees and groups of trees in forest-tundra)

At the same time, forests with dwarf shrub understorey and dwarf shrub tundra are well discernible in the QuickBird images. The research goal is to provide the transition from QuickBird to Landsat imagery in mapping the ecotone. Since a 30-meter Landsat image pixel integrates structural components of the forest-tundra zone image, forming a spectral mixture, we undertook a search for methodological approaches, that could help to separate this mixture into its constituent elements, i.e. for the methods of spectral decomposition. Several areas of research were covered.

Analysis of QuickBird images subsets corresponding to the Landsat image pixels

A detailed component-wise analysis of QuickBird image has been completed within 30 × 30 m areas, corresponding to the Landsat image pixels (Fig. 8). For each of the 8 types

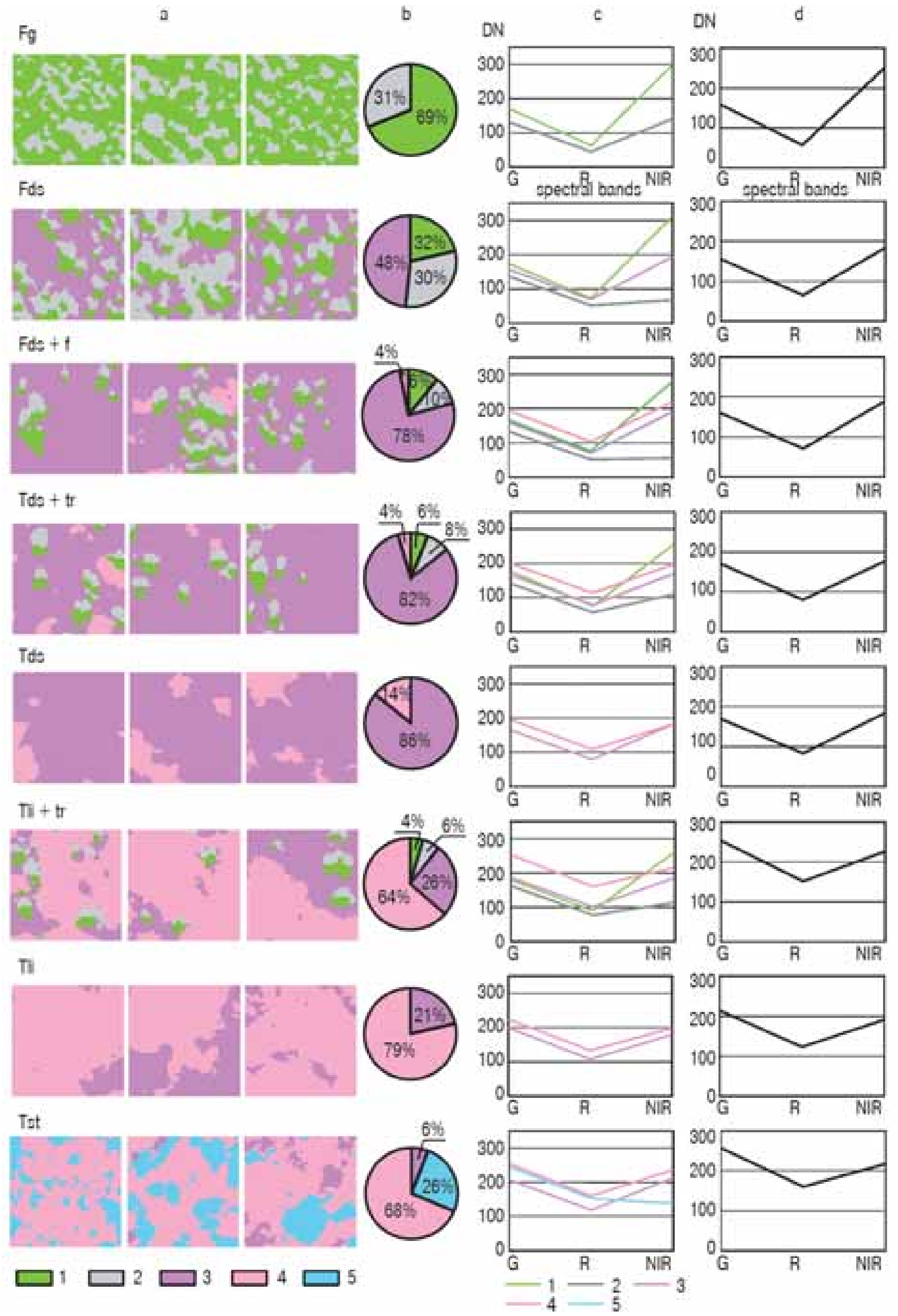


Fig. 8. Display of ecosystems components (EC) of forest-tundra in a Landsat image pixel: a snapshot analysis of QuickBird image for 8 types of ecosystems:

Fg – grassy forest; Fds – forest with dwarf shrubs; Tds + f – dwarf shrub tundra, with groups of trees; Tds + tr – dwarf shrub tundra, with individual trees; Tds – dwarf shrub tundra; Tli + tr – lichen tundra with individual trees; Tli - lichen tundra; Tst - rocky tundra [Kravtsova, Loshkareva, 2010b].

A - Results of the classification of EC in QuickBird image 30 × 30 m subsets: 1 – trees, 2 – tree shadows, 3 – dwarf shrubs, 4 – lichens, 5 – rocky surfaces; B – Percentage areas of EC (average for 3 image subsets); C – Spectral signatures of EC (average for 3 image subsets): 1 – trees, 2 – tree shadows, 3 – dwarf shrubs, 4 – lichens, 5 - rocky surfaces; D – Spectral signatures of EC mixtures for each of the 8 types of ecosystems of ecosystems in the region a few typical plots of this size were selected and classified to delineate main image components of the ecosystem: tree crowns and their shadows, dwarf shrubs, lichens, rocky surfaces (Fig. 8A). Percentage ratios of these components in each ecosystem type were computed (Fig. 8B). Spectral signatures of the components were derived from the QuickBird image (Fig. 8C) and spectral signatures of the mixtures of these components as reproduced in the Landsat images were also collected (Fig. 8D). Analysis of component spectral signatures and their "mix" in a Landsat image pixel helped to answer why the northern limit of forest is not visible in the Landsat images.

The reason is in the summary radiance of tree crowns and their shadows (Fig. 9): the high radiance of illuminated tree crowns summed up with low radiance of tree shadows give average values of radiance which are very close to those of the dwarf shrub understorey in forest and of dwarf shrub tundra [Kravtsova, Loshkareva, 2010].

Ground spectroradiometry experiments to determine how different proportions of taiga-tundra ecotone components influence the spectral signature of a resulting mixture

To determine how various quantities of components of the taiga-tundra ecotone influence the spectral image of the resulting mixtures, A.I. Mikheeva and A.E. Novichikhin conducted a full-scale ground spectroradiometry experiment in Khibiny mountains. Mixtures with controlled and systematically varied quantities of stones, lichens, dwarf shrubs (*Betula nana* and *Empetrum nigrum*), spruce (Picea avies) and birch (Betula tortuosa) branches, 299 mixtures in total, were measured by a 4-band radiometer, covering visible and near infrared part of the spectrum. This revealed combinations of ecotone components, which are separable in satellite images by the spectral characteristics, and enabled modeling of their color in colour composite images [Mikheeva et al., 2012].

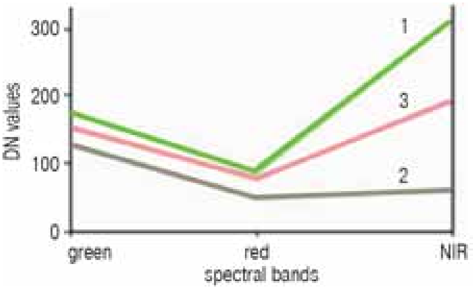


Fig. 9. Spectral characteristics of components of the forest-tundra ecosystem:

1 – trees, and 2 – tree shadows, 3 – dwarf shrubs [Kravtsova, Loshkareva, 2010b]

Spectral decomposition approach to mapping the structure of the taiga-tundra ecotone

Taking the results of ground spectroradiometry experiment as a starting point, A.I. Mikheeva [2011b] has developed a method for mapping ecotone vegetation with 15–30-m resolution Terra ASTER images (using VHR images for verification of ASTER training data and for accuracy assessment of the final map). The resulting vegetation maps show quantitative ratios of ecotone components at the subpixel level in different vegetation types. The map compilation method is based on the spectral decomposition on the basis of adaptive mixture filtering (Mixture Tuned Matched Filtering – MTMF), a technique designed to highlight a limited number of objects on the background of other objects. Because the ASTER image has only nine spectral bands with a resolution of 15–30 m, and many of them are highly correlated, only five types of objects were mapped: rocky tundra, lichen tundra, dwarf shrub tundra, birch scrub, birch-spruce forest.

To reduce interpretation errors, the territory is classified only after preliminary division with the special masks. On the basis of spectral end-members (pure spectra of specific ecotone components) the MTMF algorithm created five abundance images for the main types of objects (abundance translates into % fraction of the area occupied by the object in each pixel). These images have been verified and normalized (so that areas of all objects within each pixel sum to 100%). Accuracy assessment using reference VHR-images (in more than 15 thousand points) proved acceptability of the developed technique. The compiled map of the modern state of the vegetation ecotone, indicating the area percentage of the basic types of objects in each map class, can be used to monitor long-term changes in the structure of ecotone, when the changes exceed certain thresholds.

Decomposition approach to mapping canopy closure of tree stands

Another alternative decomposition approach was applied to map the structure of the taiga-tundra ecotone in another area, the Ary-Mas site on the Taimyr Peninsula, where this structure has a different character. While the forest-tundra of the Kola Peninsula is characterized by a mosaic of rocky, lichen and dwarf shrub tundra patches with islands of birch woodlands, in Taimyr study area the forest-tundra zone is formed by very sparse larch forests and single larches on the flat surface of the tundra, where nanomosaics of vegetation cover are too homogeneous to be seen as patches in the satellite images. The spatial structure of the images is determined by tree crowns and crown shadows on a relatively monotonous background of lichen-dwarf shrub cover. The hatch structure of tree shadows in VHR images with different hatch densities causes different brightness of the corresponding pixels in the Landsat TM image. The research challenge here is to find a relationship between the brightness of the Landsat TM pixel and quantitative characteristics of stand density and canopy closure.

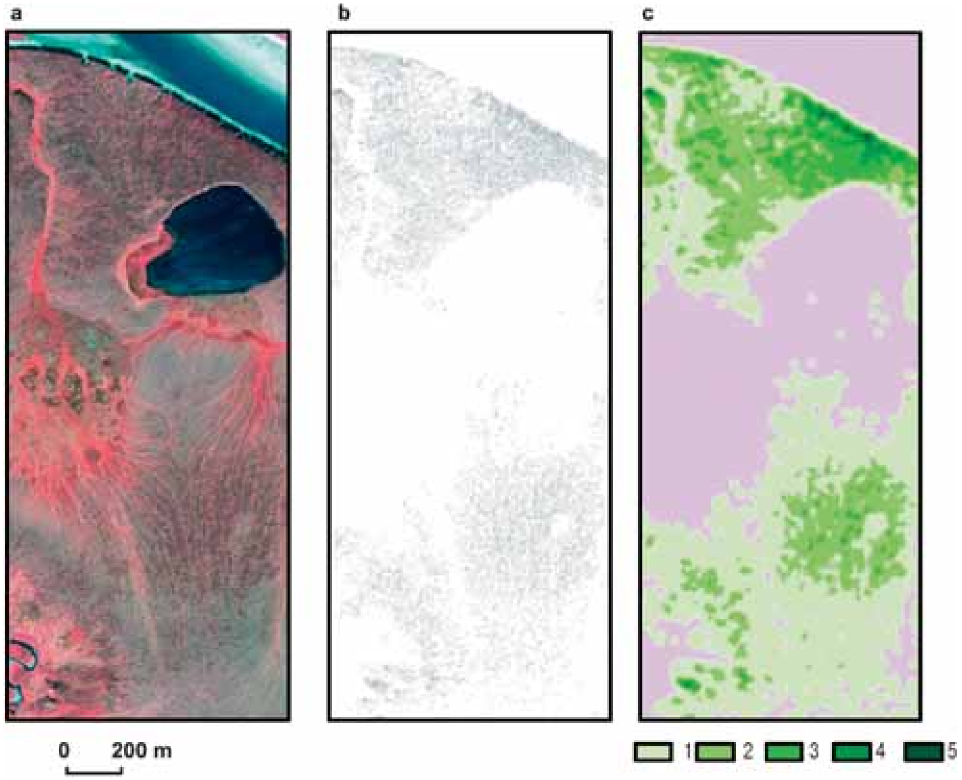


Fig. 10. Shadow mask for the very sparse larch forests in the Ary-Mas site, Taimyr, extracted from Ikonos satellite image, and the derived map of tree stand canopy closure [Tyukavina, 2011]:

a – satellite image subset, b – shadow mask, c – map of canopy closure.
Canopy closure classes: 1 – <0.05, 2 – 0.05–0.10 3 – 0.10-0.15, 4 – 0.15–0.20, 5 – > 0.2

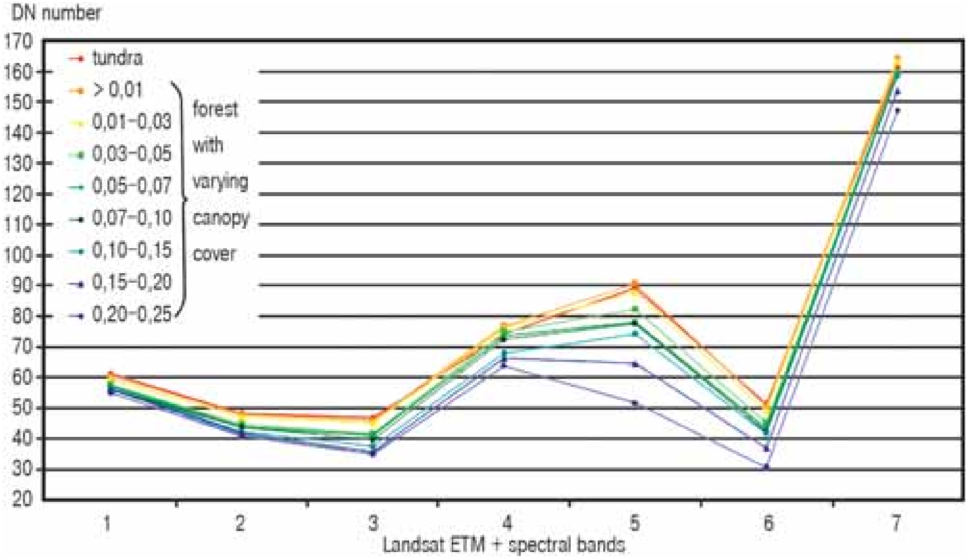


Fig. 11. Spectral signatures of tundra, very sparse and sparse larch forests derived from a Landsat TM image of Ary-Mas site [Tyukavina, 2011]

A.Yu. Tyukavina was able to find such a connection for the Ary-Mas site using field data, and to develop a methodology for mapping canopy closure with Landsat TM satellite images [Tyukavina, 2011]. For this purpose, trees shadows in the Ikonos image were extracted from the image (a "shadow mask" was created using a special technique developed by A.E. Novichikhin) and the ratio between tree crown and tree shadow areas was computed (tree crowns were mapped through a ground survey and tree shadows from the Ikonos image mask). This ratio was about 1:2 for the Ikonos image of Ary-Mas. This allowed to move from mapping tree shadows to estimating tree canopy and then canopy closure within the Ikonos image (Fig. 10).

Further, for test sites with different closure classes within the canopy closure map, the corresponding Landsat TM pixels were identified. The analysis of spectral signatures for these pixels identified a relationship between canopy closure and radiance in the middle infrared band (Fig. 11).

This enabled to make a canopy closure map from the Landsat TM image, both for the Ary-Mas site (Fig. 12) and for the whole region covered by the TM image. Thus the transition from Ikonos to Landsat TM imagery was effected for this type of the ecotone, where the ecotone spatial structure is defined by tree canopy closure. The decomposition approach here included finding the relationship between the TM pixel radiance, corresponding tree shadow area, crown area and finally tree canopy closure.

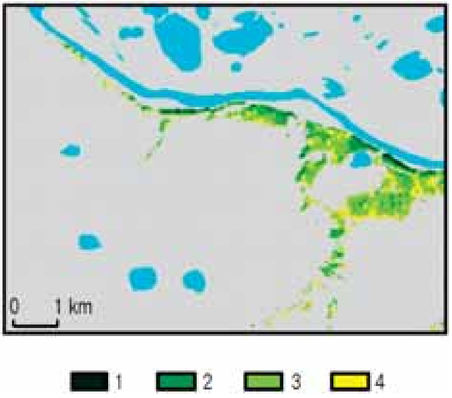


Fig. 12. Map of tree stand canopy closure for the Ary-Mas site, made on the basis of a Landsat TM image [Tyukavina, 2011]. Crown density classes:

1 – > 0.2; 2 – 0.1–0.2; 3 – 0.05–0.1; 4 – 0.03–0.05

However, as is the case with patchy tundra of the Kola Peninsula, the developed method can be recommended for further monitoring of the dynamics of ecotones in the future, but it can not be applied for retrospective studies of the ecotone dynamics in the preceding period of warming, because the older Landsat MSS images did not have the middle infrared band, and in addition, there were no VHR images to provide reference images for different canopy closure classes.

Comparison of multitemporal NDVI vegetation index images

Since the methodological findings of our research turned out to be effective for the future, long-term monitoring, but failed to study the changes in the past, for retrospective studies of vegetation dynamics we had turn to the tried and tested, simple and universal methods to study the state of vegetation, namely the calculation of the normalized

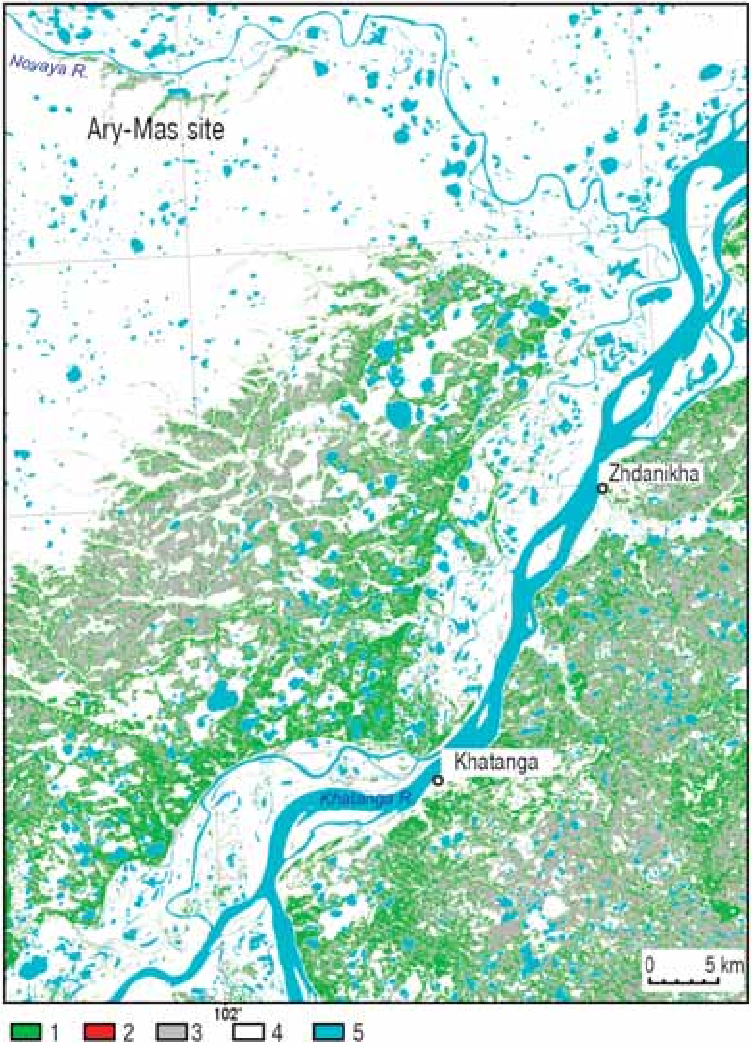


Fig. 13. Map of changes in the canopy closure of tree stands in the Khatanga River basin in 1973-2002, compiled by multitemporal NDVI differencing [Tyukavina, 2011]. Changes in canopy closure of stands from 1973 to 2002:

1 – increase; 2 – reduction; 3 – no change; 4 – non-forested areas; 5 – water bodies

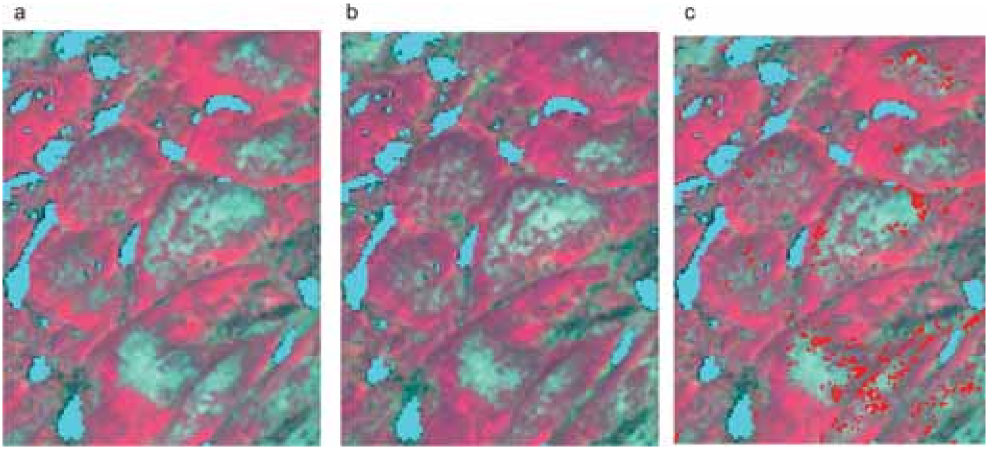


Fig. 14. Changes in vegetation at the Kanentiavr site in the north of Kola Peninsula in 1986–2005, identified by multitemporal NDVI differencing. The red color shows the advance of dwarf shrub tundra into the lichen tundra on hill summits [Loshkareva, 2011]:

a – subset of a Landsat TM image of 1986; b – subset of a Landsat TM image of 2005; c – changes overlaid onto subset of a Landsat TM image of 2005

difference vegetation index (NDVI), and to study the dynamics of vegetation – to differencing of multitemporal NDVI images. However, for the effective application of this method is necessary to separate the identified changes in the vegetation into those of interest in this study, i.e., related to climate variations, and changes caused by other factors.

Multi-temporal NDVI differencing for detection of vegetation changes over a period of warming was tested in both area, in Taimyr and in Kola Peninsula.

For Taimyr, where the change (increase) in NDVI values means an increase in canopy closure, or stand density, with the growth of shrub layer, it is important to separate in the image the areas of tree stands from the spectrally similar hummocky and polygonal tundra, where forms of meso-and microrelief determine the shadow spectral component of the tundra image, bringing it closer to the spectral image of sparse forests.

A.Yu. Tyukavina proposed a technique using the winter-spring image, where tundra is under snow cover, and as a result forest and woodland areas are well separated from the tundra. Such images with snow cover are used to prepare a mask of non-forest areas. Further analysis of spectral feature changes is conducted only for the areas of forests and woodlands on the basis of multi-year NDVI differencing [Tyukavina, 2011]. The study showed an increase in canopy closure on low terraces of the Khatanga River (Fig. 13), which is consistent with results obtained by other methods in the study of V.I. Kharuk and others [Kharuk et al., 2006].

For the Kola tundra area near Lake Kanentiavr a whole chain of operations was required to select target changes among all those detected by NDVI differencing. In the method developed by A.R. Loshkareva, restrictions were placed on the stage of the image selection (identical image dates in different years, the analysis of weather conditions preceding the survey), and at the stage of processing (mandatory implementation of radiometric correction, masking non-vegetation objects – lakes, snow fields, clouds and their shadows – to exclude them from the analysis). At the stage of interpretation, certain vegetation changes were also excluded, such as those due to differences in weather conditions during image acquisition (in particular, the areas near persisting snowfields), and anthropogenic changes. As a result, increasing values of NDVI were identified for a large territory, corresponding to the increase in the density of dwarf shrub vegetation on the borders between dwarf shrub and lichen tundra, and dwarf shrub tundra advance into the lichen tundra (Fig. 14) [Loshkareva, 2011].

CONCLUSION

The experience of studying the dynamics of the northern forest limit and taiga-tundra ecotone structure in the context of climate variations on the basis of ground and remote sensing methods, performed in the Laboratory of Aerospace Methods of the Department of Cartography and Geoinformatics MSU within PPS Arctic project, has shown considerable methodological difficulties in approaching this problem through currently available remotely-sensed data. Additional complications are caused by regional differences in the structure of the tundra-taiga transition zone, stretched for thousands of kilometers from west to east over the vast territory of Russia. A number of regionally adapted approaches had to be developed. On their basis, we have obtained new data on changes of northern vegetation during the recent decades of warming. In particular, advance of treeline by 30 meters up the slopes of the Khibiny mountains, increased stand density of tree and shrub vegetation in the forest-tundra zone of the lowland northern Kola Peninsula, where lichen-dwarf shrub tundra has also advanced into lichen tundra, and increased stand density of sparse and very sparse larch forests in the Khatanga River valley in southern Taimyr Peninsula have been identified.

Our research of the dynamics of the northern forest limit has shown significant difficulties in identifying this dynamics by remote sensing. To solve this problem we involved the newest satellite imagery available, developed new image processing techniques, and obtained some results, so far at local scale. Along with this it is prudent to outline directions for further research. To assess the impact of global climate change on the taiga-tundra ecotone, of course, the most attractive coverage for mapping is circumpolar. The first example of a preliminary circumpolar map based on Terra MODIS satellite images and the derivative images of canopy closure, VCF (Vegetation Continuous Fields) has been presented in 2011 by K. Ranson and others (Ranson et al., 2011) (Fig. 15).

This map, created in the NASA Goddard Space Flight Center, shows the distribution of the taiga-tundra ecotone, which includes patches with forest cover of 5–20% (TTE Class 1) and less than 5% (with standard deviation of more than 5%, TTE Class 2, treated as areas of potential advancement of woody vegetation in the tundra). However, the accuracy of this map when checked against airborne laser profiling data is estimated by the authors only at 67,7%.

We carried out validation of this map against Russian thematic maps for the whole country and against local site interpretation maps compiled from VHR satellite images [Kravtsova, Tutubalina, 2012]. We identified that this map displays the distribution of the taiga-tundra ecotone well only in European part of Russia, but does not portray it correctly in the Asian part of the country. In the category of 5–20% forest cover, considered as ecotone, dwarf birch tundra and tundra bogs are included, which are in fact located north of the ecotone. An even greater discrepancy is the inclusion into the forest-tundra zone of northern and even temperate sparse larch forests of Siberia, distributed at distances of 600–1000 km south of the ecotone boundary. It is true, however, that among the Russian landscape scientists of different scientific schools similar efforts of ‘expanding’ the forest-tundra have been noted [Makunina, 2004]. We conclude that this circumpolar map is of interest as a data source portraying the northern forest canopy closure, but it cannot be used directly to monitor changes in the taiga-tundra ecotone.

This brings us to the future objectives to address the dynamics of the northern forest

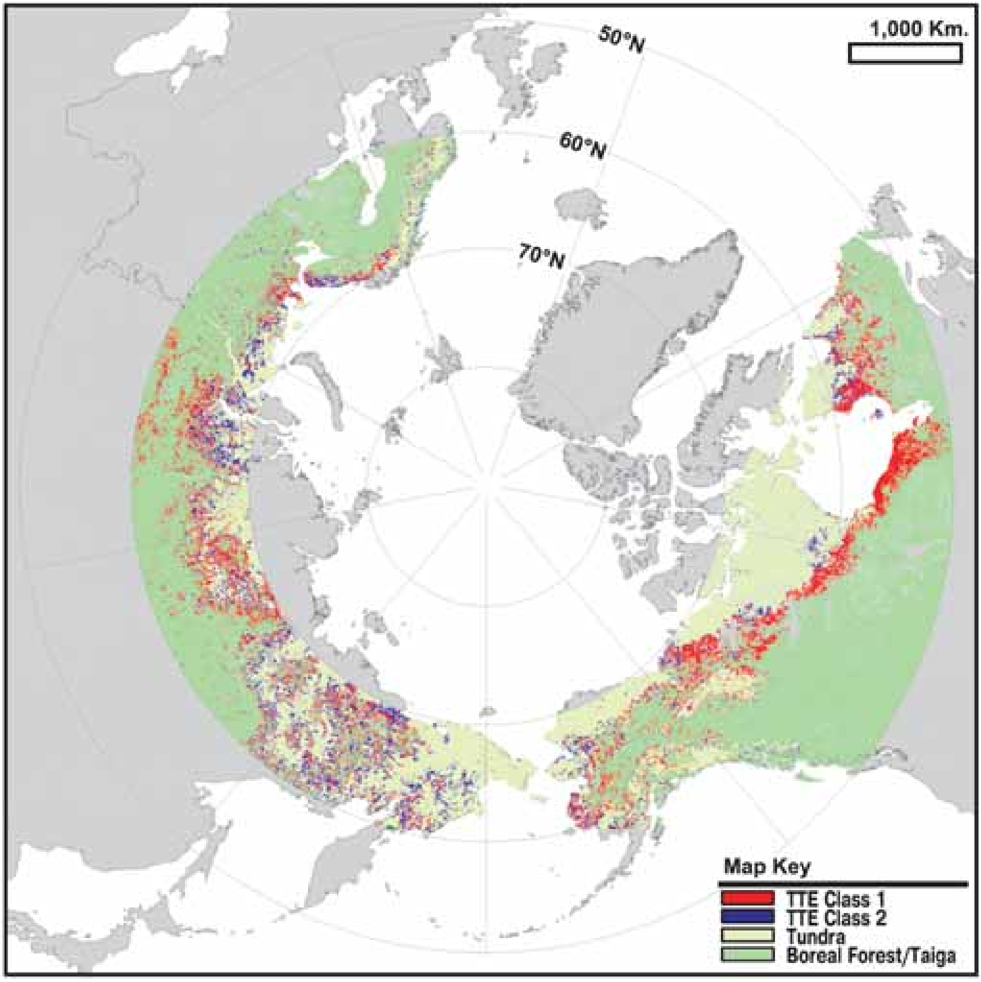


Fig. 15. Circumpolar map of the taiga-tundra ecotone, produced in the U.S. [Ranson et al., 2011]

limit at different scale levels. In the field of global mapping of the circumpolar taiga-tundra ecotone, the research should focus on improving regional calibration of wide-coverage satellite data, and clarify the boundaries of physiogeographic regions themselves, taking into account the species composition of forest stands, the characteristics of ground cover, topography, moisture regime.

At the regional level, mapping the ecotone with spaceborne hyperspectral imagery (e.g. EO-1 Hyperion), and with combination of optical and radar satellite images should be tested. At the local level it is needed to expand the network of reference sites for field support of the more generalized levels of mapping.

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