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THE USE OF SPACE INFORMATION ABOUT THE EARTH

Capabilities of Multispectral Satellite Data in an Assessment of the Status of Abandoned Fire Hazardous and Rewetting Peat Extraction Lands

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Abstract—The capabilities of several multispectral satellite data types to identify the status of peatlands affected by peat extraction and abandoned deposits are examined to assess potential fire dangers and rewetting effectiveness. The available level of detail of describing land/vegetation cover for monitoring abandoned peat extraction sites using Spot-5 HRG, Spot-6 HRG, and Landsat-7 ETM+ satellite images has been demonstrated using the example of peatlands in the Meschera National Park (Vladimir oblast). The results reflect the pros and cons of using different data types to analyze the status of abandoned peat-extraction lands for purposes of peatland inventory, land-cover monitoring, and the prioritization of sites subject to rewetting and mire restoration, as well as for an evaluation of the effectiveness of these measures.

Keywords: remote sensing, multispectral images, peatbogs, peatlands, peat extraction lands, vegetation cover, forest–peat fires, rewetting

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INTRODUCTION

Peat bogs, together with paludified shallow peat lands, occupy more than 20% of the territory of Russia (Vomperskii et al., 1996, 2005, 2011) and, in many regions, are substantially changed by anthropogenic activities (*A Quick Scan*..., 2009). The strongest influence on marshes is caused by the extraction of peat, especially by the milling method—the most common industrial way of obtaining this raw material in most countries. Unlike the open-pit and other so-called "wet" methods of peat extraction widespread until the middle of the 20th century, in which the abandoned workings were independently filled with water and gradually turned into swamp, the milling method involves the intensive drainage of the extraction areas and, accordingly, the necessity of their subsequent reclamation. In total, by various estimates, from 850000 to 1.5 million ha of peat bogs were disrupted in the country during the extraction of peat, which, after the normative depletion of the deposit, were for the most part reclaimed for agriculture use (including private gardening) and, less often, for forestry and other tasks (*Torfyanye bolota*..., 2001).

By the beginning of the 1990s, approximately 250000 ha of peatlands was used, mainly for milling peat extraction; the estimate is approximate due to specifics of the accounting (*Torfyanye bolota*..., 2001). Subsequently, after the closure or suspension of the operation of the enterprises, significant milling peat extraction areas were abandoned without the required deplition of the deposit and the necessary reclamation. Due to strong drainage, the vegetation cover formed on them extremely slowly: more than 20 years after the ceasing of peat extraction, areas of bare peat are preserved on the fields of milling extraction. There are intensive destruction and decomposition of peat, water and wind erosion, and the emission of carbon dioxide into the atmosphere. Here, the probability of peat fires is greatest (Minayeva and Sirin, 2002, Sirin et al., 2011). This is one of the most acute ecological problems associated with peat bogs in the country (*Action Plan*..., 2003, *A Quick Scan*..., 2009), which may intensify due to climate change (*Assessment*..., 2008; Minayeva and Sirin, 2011). Drained peat bogs and peat fires are one of the significant anthropogenic sources of greenhouse gases entering the atmosphere (*IPCC*, 2014).

The most effective way to prevent unfavorable processes and reduce the fire danger of such lands, in the absence of grounds for their return to economic circulation, is their rewetting and artificial bogging (Water Code of the Russian Federation, 2006, Article 52). Given the scale of the problem, this requires the identification of priority objects for watering, as well as the organization of subsequent monitoring to assess the effectiveness of the specified activities. In this case, abandoned peat extraction lands are of considerable size, heavy-going, and difficult for ground mapping. Their vegetation cover is characterized by high spatial heterogeneity and multidirectional dynamics, including due to the sensitivity to the climatic conditions of individual years and the periodic impact of peat fires. Therefore, satellite observation data appear to be the most promising and practically realizable system for monitoring the effectiveness of abandoned peat extraction lands, even taking into account already existing methods of remote sensing. A regular survey from space allows monitoring the status of peat-extraction lands, planning and controlling measures for their rewetting, and estimating the effectiveness of these activities.

The principles of such an approach based on the Landsat-5/7 data have already been tested on the example of the peatlands of the Meshchera National Park, Vladimir oblast (Medvedeva et al., 2011). However, in 2010, extensive fires in the central regions of the European part of Russia (Sirin et al., 2011) have shown the need for the further development of methodological approaches to the use of remote sensing for solving problems of assessing the state of fire-dangerous peat bogs and rewetting efficiency (Sirin et al., 2014, 2014b, 2014c). At least 2- to 3-fold satellite data coverage is required to organize the constant monitoring of peatlands in a fire-dangerous period (from spring to autumn). Experience shows that, even in a region such as Moscow oblast (which is covered with satellite data very often), operative imagery from various high-resolution resource satellites is very fragmentary in time and space, and even ordering a commercial imagery at a given interval and with high priority of areas does not guarantee it will be obtained using a single satellite system (Sirin et al., 2014a). In connection with this, the possibility to simultaneously use not one, but two or three satellite systems which can complement each other is of particular relevance.

In this paper, the goal was to identify the available degree of detailing land cover types for monitoring abandoned peat-extraction lands on the basis of various satellite images of Spot-5 HRG, Spot-6 HRG, and Landsat-7 ETM + (also characterizes the Landsat-8 capabilities) to determine their state and analyze the changes that occur as a result of rewetting and secondary bogging.

OBJECTS AND METHODS OF RESEARCH

The research was carried out using the example of the objects of the Meshchera National Park (NP), within which there is one of the largest peat bog complexes in European Russia disturbed by peat utilization of different periods and with the use of different peat extraction technologies, including milling (Medvedeva et al., 2011). The NP, which was established in 1992 in the Gus-Khrustalny raion of Vladimir oblast, adjoins the eastern border of Moscow oblast, and a vast variety of peatbog ecosystems of the Meschera Lowland is represented on its territory with an area of 118 700 ha, including 62 large wetlands. Due to the frequency of exposure to forest and peat fires, the national park became a pioneer of large-scale works in our country to water the peat lands for the restoration of marsh ecosystems (Sirin et al., 2011).

The vegetation of bogs and anthropogenically disturbed peat lands has been studied in sufficient detail (Antipin et al., 2004); there are digital maps of part of the abandoned peat-extraction lands, which allowed the formation of a set of reference data for identifying types of land/vegetation cover. Since 2005, on constant sample plots of the three most representative wetlands—Borsky, Ostrovsky, and Garinsky Tasin—changes in the vegetation cover and environmental parameters are being monitored. The main tendencies and factors of the dynamics of the vegetation cover of disturbed peat lands have been revealed (Vozbrannaya et al., 2008). For the present study, nine sites in the wetlands of the national park with a total area of about 8000 ha were used.

For the research, three sets of high-resolution data were selected: Spot-5 HRG, Spot-6 HRG, and Landsat-7 ETM+ for 2013 (hereinafter, Spot-5, Spot-6 and Landsat-7, respectively). For the analysis, images obtained in the six spectral channels for Landsat-7 and in all available channels for the remaining data sets were used (Table 1). It is also necessary to note the presence of the Landsat-8 data set, which includes additional Deep Blue 0.43–0.45 μm and SWIR 1.36–1.39 μm bands relative to Landsat-7. The coverage of the study area with the Landsat-7 satellite data for 2013 was carried out using two scenes with dates of August 11, 2013, and July 1, 2013. As is known, since 2003 the ETM+ system offers scenes with gaps. Therefore, the image for 2013 was collected with a predominance of the scene for August 11, 2013, and in places for July 1, 2013.

Analysis and processing of satellite images included the following main stages:

(i) an estimation of the set of various land-cover classes necessary for recognition within the test site;

(ii) the preparation of ground reference data and results of visual expert analysis;

(iii) the preparation of a training sample for the supervised classification of satellite images;

(iv) the classification of land cover independently from the data of each satellite device;

(v) an expert assessment of study validity;

(vi) a comparison of classification results and assessment of separation of earth cover classes using different satellite images.

Previous studies (Medvedeva et al., 2011) have shown that using a set of six classes of vegetation/land

Table 1. Characteristics of the satellite data used

Data set name	Landsat-7	Spot-5	Spot-6
Resolution (pixel size), m	30	10	6
Image date	August 08, 2013*	September 13, 2013	September 13, 2013
Spectral bands	Used wavelengths, μm		
Blue	ETM+1 0.45–0.52		0.45–0.52
Green	ETM+2 0.53–0.61	0.50–0.59	0.53–0.59
Red	ETM+3 0.63–0.69	0.61–0.68	0.63–0.70
NIR	ETM+4 0.75–0.90	0.78–0.89	0.76–0.89
SWIR 1	ETM+5 1.55–1.75	1.58–1.75	–
SWIR 2	ETM+7 2.09–2.35	–	–

* The predominance of the scene for August 11, 2013, and in places for July 1, 2013.

cover is sufficient to solve the tasks set (Sirin et al., 2014b). They include (1) *bare peat*—areas of bare and burned peat, including patches with sparse vegetation cover; (2) *willow herb*, *small reed and small birch reed communities* are forming during overgrowing of bare and burned peat; (3) *communities with pine*—differently depressed pine stands; (4) *communities dominated by willow and birch*—mainly birch communities (overgrowing milled fields), occasionally with alder and aspen stands; (5) *hydrophilic communities with cat-tail and reed*—formed by hydrophilic species such as cat-tail and reed, water plantain and different cotton grasses in wet areas: *and* (6) *water surfaces*—water bodies, including those formed after natural or artificial rewetting of peatland areas. Classes 1 and 2 are characterized by the lowest swamp-water levels, a periodically severely drying-up soil surface, and the highest degree of fire danger. Classes 3 and 4 occupy an intermediate position. Class 5 is characterized by swamp water level values close to the soil surface, not representing a significant fire danger. Classes 5 and 6 form areas that will further develop as wetlands.

For the six specified classes, 12 reference plots were selected on seven of the nine wetlands on the Landsat-7 satellite image. According to the results of the ground study, the reference plots are fairly homogeneous, which allows one to form a set of reference data for supervised classification. For class 1, it was possible to choose four training sites; for class 2 and 3, one for each; for class 4, two; for class 5, three; and for class 6, one. For other satellite images, reference data was obtained from a spatial expert analysis of the previously used 12 reference areas.

For classification, Landsat-7, Spot-5, and Spot-6 images were segmented by spectral characteristics using the ScanEx Image Processor v.4.0 data processing program (ScanEx, 2011). The initial stage was a stage of rapid growth of small segments from the input pixels. The further segmentation process consisted of merging small segments obtained at the initial stage pairwise. In the case of multiband segmentation, the dissimilarity metric is calculated as the difference between the heterogeneity of the resulting segment and the heterogeneities of the source segments, weighed by the number of pixels of the corresponding segments.

Next, an interactive classification of segmented images was carried out. Segments can be considered as operational–territorial units for which the problem of assigning to thematic classes can be solved based on the calculated brightness characteristics (average brightness and dispersion in the bands). To do this, user-defined thematic information is used to classify segments of the training sample in a particular thematic class, and mathematical methods of discrimination are linear and quadratic discriminant analysis (ScanEx, 2011). To check the results of the classification, 73 points were chosen on five of the nine peatlands. The quality of the classified data was estimated based on complete error matrices and calculated accuracies of classifications (Labutina, 2004).

RESULTS AND DISCUSSION

Figure 1 presents the average values of the spectral brightness of recognizable classes of the land surface obtained on the basis of the multispectral satellite imagery used and the training sample data. Figure 2 characterizes the areas occupied by different recognizable classes in two-dimensional spaces of spectral brightness values formed by various combinations of Landsat-7, Spot-5, and Spot-6 bands most informative for the solved tasks. The illustrations provide a visual representation of the possibilities of separating the studied classes using various satellite data.

According to the spectral resolution, the Landsat-7 data having six bands with wavelengths from 0.45 to 2.35 μm provide the best class separation (Table 1, Fig. 2). It is necessary to note the advantage of Land-

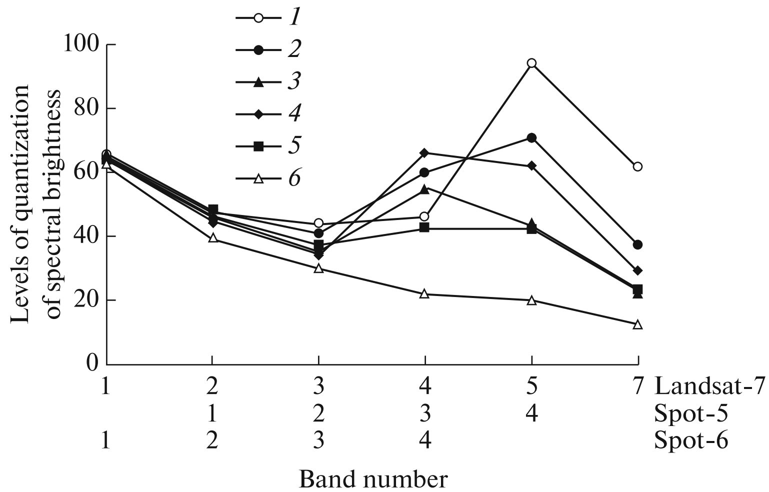

Fig. 1. Average values of spectral brightness in the bands of the data used for a set of recognizable classes: (*1*) bare peat; (*2*) willow herb, small reed and small birch reed communities; (*3*) communities with pine; (*4*) communities dominated by willow and birch; (*5*) hydrophilic communities with cat-tail and reed; and (*6*) water surfaces.

sat-8, which has two bands in addition to the set of Landsat-7 bands—No. 1 Deep Blue 0.43–0.45 μm and No. 9 SWIR 1.36–1.39 μm. The last band simplifies the search for clouds in the images. The Spot-5 data (four bands with wavelengths from 0.50 to 1.75 μm) are also acceptable for class separation considered. Both Landsat-7 (Landsat-8) and Spot-5 satellites have the necessary band for operation in the range of 1.58–1.75 μm, which, however, is absent in the Spot-6 data set (four bands with wavelengths from 0.45 to 0.89 μm). As expected, the Spot-6 data classification results showed low accuracy. Therefore, for the Spot-6 data set, an additional unsupervised ISODATA classification with 30 classes was performed (Iterative Self-Organizing Data Analysis Technique). The algorithm is based on image clustering based on the difference between the mean values of clusters (the minimum spectral distance between the centers of classes) (ScanEx, 2011). When conducting an unsupervised classification for the Spot-6 data, it was possible to improve class recognition by up to 36%.

Examples of classification results for different satellite images in a representative area are given in Fig. 3. Figure 3b illustrates a fairly close result to Fig. 3a taking into account the higher resolution and rainier season. In Fig. 3c, the location of classes differs significantly from the previous two illustrations. It is especially possible to note classes 1 and 5, the recognition of which is difficult due to the characteristics of the original satellite data. The separation of these classes is improved through an unsupervised classification, the results of which can be seen in Fig. 3d. Here, both problem classes are mostly located on the same places relative to Fig. 3b. However, together with the error matrices (Table 2), the results of the Spot-6 data classifications show their insufficient accuracy for solving problems of recognition of the studied set of land cover classes.

The accuracy of the allocation of the land-cover classes under consideration on the basis of the satellite data used can be estimated from the error matrix (Table 2). The Landsat-7 matrix is a reference classification with an accuracy of 100%. In the Spot-5 matrix, two points of the "peat" class and three points of the "grass-communities" class, mistakenly classified as hydrophilic communities, can be seen. In this case, these "errors" can be explained by the different periods in which the initial remote sensing data were obtained: the Spot-5 data is in contrast to the Landsat-7 data after prolonged rains. The first of the two Spot-6 matrices illustrates the inaccuracies in the classification of all classes. The Spot-6 matrix of unsupervised classification allows getting an idea of the degree of improvement of previous indicators as a result of using this procedure. The results are improved in almost all classes.

The not very high accuracy (62%) of the initial classification of the Spot-6 data was significantly improved using the unsupervised classification—the result is up to 81%; however, despite this, it is still not high enough. Objectively, of course, the absence of the SWIR band manifests itself. However, there is a possible subjective source of error. The comparison was made with the results of classification according to the Landsat-7 data, which were received in July–August 2013. At the same time, the Spot-5 and -6 data refer to the middle of September 2013. This period was preceded by heavy rains on the study area. This fact may explain the greater number of hydrophilic sites than detected by the Landsat data. The Spot-5 and -6 data were obtained in one time period and, in both cases, the rains had the same effect. However, according to the

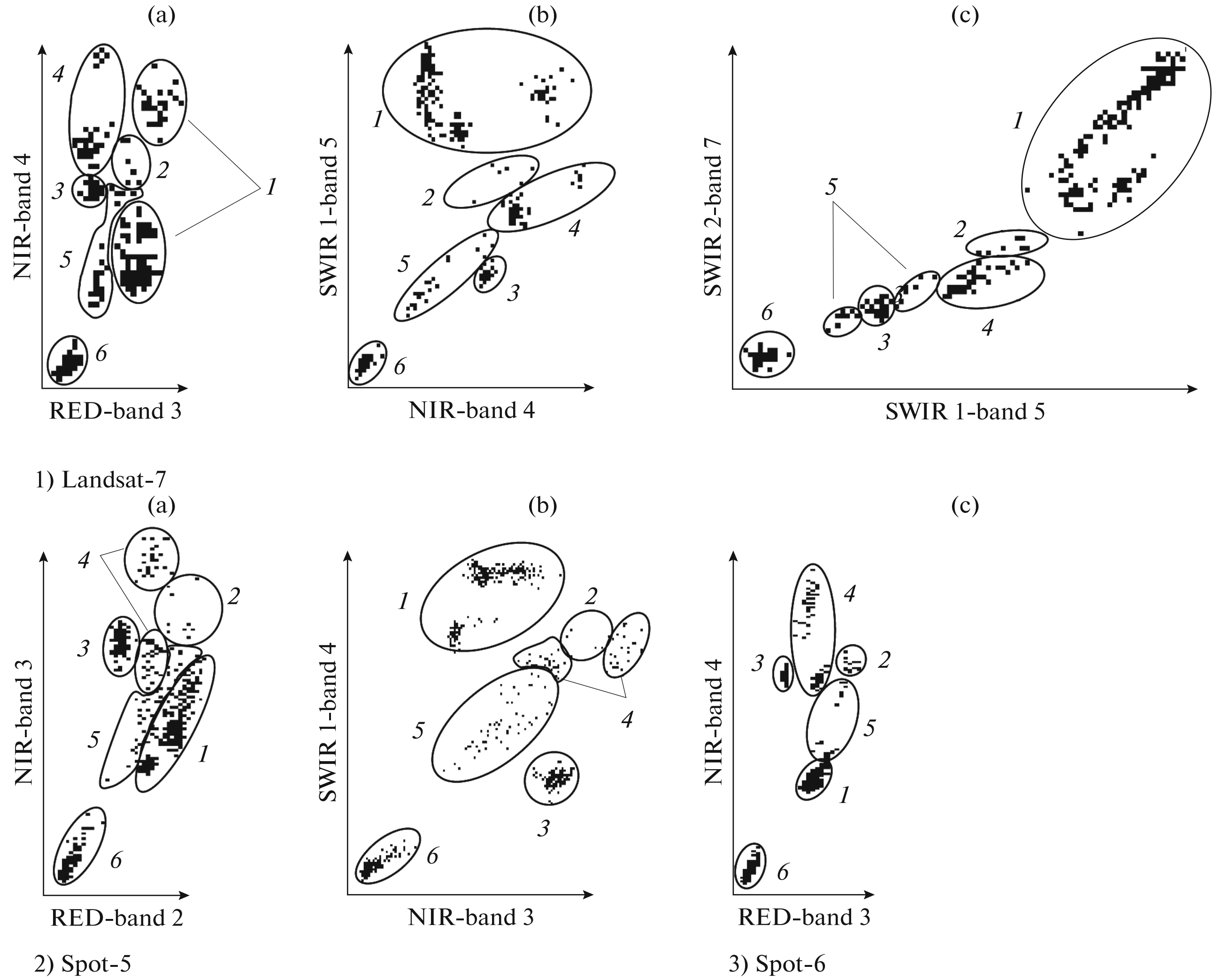

Fig. 2. Areas of different classes in a two-dimensional space of spectral brightness values for different combinations of bands of data used. See the explanations to Fig. 1.

Spot-5 data, the separation of wet peat and hydrophilic communities is more successful due to the presence of the SWIR band, the absence of which is why separation it is difficult for the Spot-6 data.

Figures 2.1a and 2.2a show the too close arrangement of the pixels of the training sample of classes in the spectral RED-NIR bands. In the following Figs. 2.1b–2.1c and 2.2b, areas of the location of these pixels are more widely distributed in space, which allows separate the classes more accurately. In Fig. 2.3, the training sites are already given taking into account the complexity of separation some of them; however, this does not solve the problem of separation the "peat" and "hydrophilic vegetation" classes in the border zone. The absence of SWIR bands in the Spot-6 data manifests itself.

When conducting an unsupervised classification for the Spot-6 data, it was possible to improve the quality of recognition of the "bare peat" class by 36%, of the "grass communities" class by 6%, of the "communities with pine" class by 12%, of the "Communities dominated by willow and birch" class by 5%, and of the "water" class by 3%. At the same time, the quality of recognition of the "hydrophilic communities" class worsened by 11%. This procedure allows one to automatically divide the image into a specified number of classes, each of which, after expert analysis, is assigned one of the land-cover classes from the set used (in this case, six classes).

A separate aspect is the spatial resolution of the compared remote-sensing data. One feature of the considered objects—peat extraction lands—is spatial fragmentation. Therefore, for peat extraction lands typical for milling, a drying network with so-called field drains dividing the sites of the developed areas with a distance between them of about 40 m is charac-

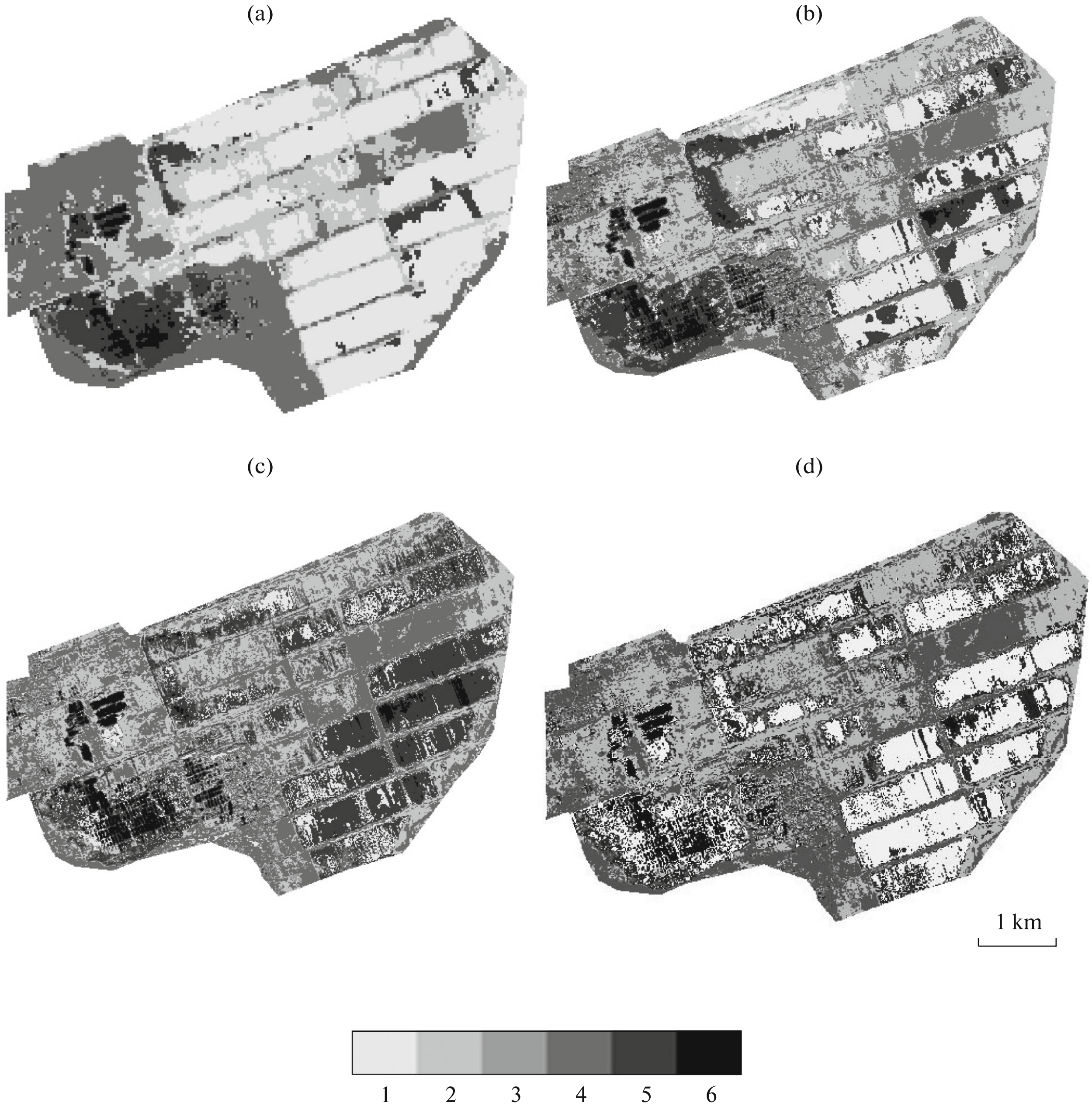

Fig. 3. Examples of the classification of different satellite images of the peat-extraction site of the Ostrovsky peatland. For notes see Fig. 1. (a) Landsat-7, (b) Spot-5, (c) Spot-6 (supervised classification), and (d) Spot-6 (unsupervised classification).

teristic. They are supplemented by collecting canals, main canals, and other elements of the drainage network. The state of the field drains in the course of time after peat extraction ceases can be different. Most often, this means different hydrophilic vegetation with areas of an open water surface. Proceeding from this, the Spot-6 data are the most suitable for solving the problems under consideration. They are the most detailed images of the analyzed set—6 m. The Spot-5 data with a spatial resolution of 10 m also allow the necessary accuracy for performing the tasks set. The Landsat-7 data is too rough (30 m) and, as is seen in Fig. 3, when using them, the accuracy of the representation of the objects under study decreases.

CONCLUSIONS

The basis for the satellite monitoring of abandoned peat-extraction lands may be the ability to recognize areas of bare peat and different types of vegetation according to their spectral characteristics measured using remote sensing instruments. The possibility of classifying land-cover types from satellite images using data from a selective ground study is shown.

Table 2. Complete error matrices and accuracy of classification results for different satellite data

Classes	Actual							
	Landsat-7 data							
Calculated	1	2	3	4	5	6	Σ	Accuracy, %
1	10	0	0	0	0	0	10	100.0
2	0	12	(")	(")	(")	(")	12	100.0
3	(")	0	13	(")	(")	(")	13	100.0
4	(")	(")	0	11	(")	(")	11	100.0
5	(")	(")	(")	0	15	(")	15	100.0
6	(")	(")	(")	(")	0	12	12	100.0
Σ	10	12	13	11	15	12	73	
Accuracy, %	100.0	100.0	100.0	100.0	100.0	100.0		100.00*
	Spot-5 data							
1	8	0	0	0	0	0	8	100.0
2	0	9	(")	(")	(")	(")	9	100.0
3	(")	0	13	(")	(")	(")	13	100.0
4	(")	(")	0	11	(")	(")	11	100.0
5	2	3	(")	0	15	(")	20	75.0
6	0	0	(")	(")	0	12	12	100.0
Σ	10	12	13	11	15	12	73	
Accuracy, %	80.0	75.0	100.0	100.0	100.0	100.0		93.15*
	Spot-6 data. Supervised classification							
1	1	2	0	1	2	0	6	16.7
2	0	4	(")	0	1	(")	5	80.0
3	(")	0	10	2	0	(")	12	83.3
4	2	6	3	8	1	(")	20	40.0
5	7	0	0	0	11	1	19	57.9
6	0	(")	(")	(")	0	11	11	100.0
Σ	10	12	13	11	15	12	73	
Accuracy, %	10.0	33.3	76.9	72.7	73.3	91.7		61.64*
	Spot-6 data. Unsupervised classification							
1	8	0	0	0	4	0	12	66.7
2	1	8	(")	(")	0	(")	9	88.9
3	0	0	10	(")	(")	(")	10	100.0
4	(")	(")	3	11	1	(")	15	73.3
5	1	4	0	0	10	(")	15	66.7
6	0	0	(")	(")	0	12	12	100.0
Σ	10	12	13	11	15	12	73	
Accuracy, %	80.0	66.7	76.9	100.0	66.7	100.0		80.82*

* General accuracy of classification.

The analyzed satellite images make it possible to classify cover types, the thematic details of which are quite sufficient for solving the problem of monitoring areas of abandoned peat-extraction lands. The high spatial variability of land cover of abandoned peat lands revealed in this work can serve as a visual justification for the need to develop and use remote monitoring methods.

The results of an analysis of the possibilities of using multispectral satellite images have shown the insufficient potential of the Spot-6 data for solving problems of monitoring the state of abandoned peat-extraction lands with the required degree of detail. The main problem of these and similar data in the spectral sense is the mixing of diametrically opposite (from the point of view of monitoring tasks) sections of bare peat with areas of hydrophilic vegetation and other types of vegetation cover. This calls into question the effectiveness of using such data to solve the tasks set with the necessary accuracy and reliability.

The Landsat-7 data opens up the potential for the regular monitoring of developed peatlands, both at the level of individual wetlands and larger areas, with a solution for the task of determining the level of potential fire risk; however, significant limitations are caused by parts of the image missing due to a malfunction of the SLC device. The disadvantages of Landsat-7 are filled with Landsat-8 data capabilities. However, it is worth noting that, due to the insufficient frequency of the actual imagery and the presence of clouds, it is not always possible to obtain even one image for the analyzed object during the growing season.

The Spot data line potentially provides the imagery frequency for Spot-5 once in 2 to 3 days, and, for Spot-6 in the grouping with Spot-7, every day. In addition, it was determined that differences in the various types of land cover are revealed in the Spot-5 data set no worse than in Landsat-7, and sufficiently to solve the task set. Unfortunately, on March 29, 2015, the satellite was decommissioned. However, there is still the potential for using the Spot-5 data for a retrospective analysis of the state of the studied objects.

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