New information technology for phytocenoses regional monitoring using remote sensing data

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Abstract

A new information technology for plant communities monitoring using remote sensing data, oriented for application at the regional level, is proposed. The technology is based on maintaining a base of reference polygons, accumulating data on the boundaries of specific plant communities and related semantic information. This database provides a source of verified and up-to-date information for solving problems of rational nature management. To expand the database of reference polygons, two algorithms for finding new ones are presented: a reliable algorithm (analyzing several growing seasons) and an urgent algorithm (based on the current growing season). The advantage of the proposed system is the integration of data storage, processing, and analysis, which enables the automation of the creation of new and the monitoring of existing polygons, as well as the solution of a wide range of problems based on remote sensing data and artificial intelligence algorithms. Practical tasks in studying of phytocenoses in the Samara Region, implemented using the proposed monitoring technology, are considered: updating forest inventory data, monitoring the status of a rare reintroduced species (Paeonia Tenuifolia), searching for new reference polygons across a vast territory of several steppe protected areas, and searching for areas of presence of an invasive plant species (Elaeagnus angustifolia L).

Keywords: information technology, phytocenoses monitoring, Earth remote sensing, geoinformation system, reference polygons, classification.

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Introduction

The implementation of measures of rational environmental management requires the accompaniment of data obtained during the monitoring of plant communities (phytocenoses): forests, meadows, steppe communities, etc. [1, 2]. At high anthropogenic transformation of landscapes, which takes place in the Samara region, natural phytocenoses are fragmentary and can occupy small areas [3]. Their identification among anthropogenic spaces, as well as subsequent field surveys, requires a lot of labor and time [4]. Field surveys are even more difficult when covering large areas.

In such a situation, thematic analysis of remote sensing (RS) images is an effective substitute for field studies [5]. Modern remote sensing systems allow obtaining data with various characteristics: in terms of spatial resolution, swath width, number and spectral range of channels. For joint analysis of heterogeneous images, storage of monitoring results in raster and vector form, and planning of future studies, it is natural to use the capabilities of modern geographic information systems (GIS).

Machine vision algorithms used for thematic analysis of remote sensing images cannot be configured without training data. The importance of this stage is admitted by many researchers [6, 7]. The results of field research [8, 9], the results of interpretation of remote sensing images by experts [10], as well as historical information in the form of thematic maps [6, 11, 12] can serve as a source of training data. Of particular interest are works combining several sources of data collection, as well as those aimed at optimizing the process of forming a training set [6, 7, 13]. The present work contributes to a rational combination of field research and the use of artificial intelligence to solve environmental management problems.

In this paper, we describe an approach to automated monitoring of phytocenoses, carried out at the regional level. It is based on the handling of a base of reference polygons, which accumulates verified data on the boundaries of certain plant communities and semantic information about them. This database serves as the basis for searching for new territories with a certain type of vegetation (both valuable and invasive), identifying and analyzing the causes of vegetation changes, and planning environmental protection measures. Within the framework of the proposed technology, considerable attention is paid to monitoring using satellite images. The algorithm for searching for new reference polygons based on a series of medium-resolution multitemporal images, which does not require radiometric matching of images acquired in different imaging conditions, is considered in detail. The results of testing the algorithm for plant communities of the steppe zone of the Samara region in the territory of protected areas of regional importance are presented. Namely, the algorithm for searching for new reference polygons is presented in two versions: reliable with the analysis of several growing seasons and urgent for the current growing season.

1. Description of information technology for phytocenoses monitoring

The proposed information technology (Fig. 1) is based on the support and replenishment of a base of reference polygons containing polygonal and point objects describing the position of homogeneous plant communities. For each reference polygon (or point), information on community type (woody, shrub, herbaceous), its value (valuable, invasive, other), characterization (listing of dominant species with indication of rare and invasive plants), date of ground visit, photos and other information is stored.

In accordance with the given scheme, GIS provides necessary data to computing blocks, as well as the storage of intermediate and final information. If necessary, RS image is linked to the existing digital map of the territory. Based on RS image (or the series of images) and auxiliary information (elevation model, climatic data, etc.) a set of features is formed. The classifier is training using reference polygon data (and vector layers if necessary). The results of thematic classification of the territory are fed to the input of the analysis block. In particular, for the task of searching for new reference polygons, the selection of areas whose class corresponds with high confidence to the class of valuable plant communities is performed (i.e., the features for candidates for new reference polygons correspond well to the features within the reference polygons of the database). The new sites are then sent for verification by field surveys and, if confirmed to be valuable and belong to a particular vegetation class, are added to the regional reference polygon database. It is important to note that the field survey is not conducted over the entire territory, but only in localized areas, which significantly reduces both the time and cost of the survey process.

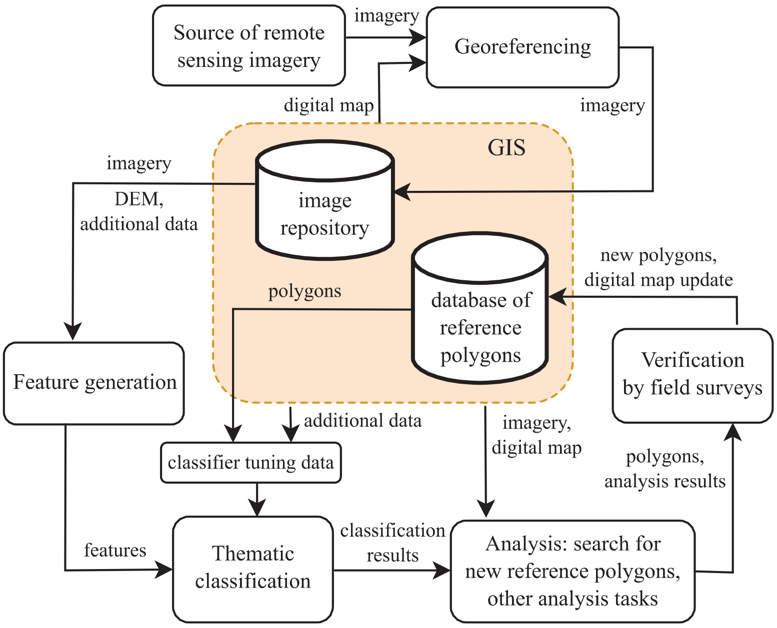


Fig. 1. Scheme of information technology for phytocenoses monitoring

The specific algorithmic content of the analysis block depends on both the vegetation type and the monitoring objectives. For example, analyzing the variability of a valuable vegetation community within a reference polygon in progress of time (e.g., NDVI variance) may indicate its degradation or change of the dominant species. An increase in the number of points corresponding to an invasive plant species class indicates its overgrowth and suppression of natural species. The identified mismatch between the forest inventory data and the results of forest vegetation classification shows the loss of relevance of the reference information [12]. The found changes require closer study by ecologists, including analysis of the causes and field visits to fix the actual state of vegetation.

The developed information technology for phytocenoses monitoring is largely universal. For its practical implementation at the regional level, we use the assumption that the main RS data sources are medium resolution images (5-20 meters in one pixel). In this case, the significant part of the territory of many Russian constituents can be imaged almost simultaneously (during one spacecraft flyby). So, the imaging conditions of reference polygons and the rest of the monitoring territory will be the same. And there is no need to adjust images with different imaging conditions before passing them to the classification procedure. If this condition is not met, it is necessary to add an image adjustment block.

Thus, the following conditions of the use of the information technology of monitoring can be emphasized:

1. The monitoring area and reference polygons used for a specific task are completely covered by a single-path space imagery, i.e. they are sensed almost simultaneously. For Sentinel-2 images the width of the sensed swath is 290 km, and the distance between the two most remote points of the Samara region is about 330 km. Thus, this condition is feasible even considering the existence of fixed nadir imaging swathes of spacecraft (in case of the absence of camera rotation).
2. A regional GIS is operating in the territory, within the framework of which it is possible to maintain (and expand) a phytocenoses database in the form of a graphical layer and associated semantic data (vegetation characteristics). The GIS is also used as a source of cartographic data required for the monitoring phases.

3. There is a number of pre-identified or artificially created area objects ("reference polygons") with known (verified) vegetation characteristics on the monitoring territory.
4. The territory has the necessary transportation infrastructure. So, the final (field) study and verification of new phytocenoses identified in the course of monitoring can be to carried out without significant costs.

The above requirements are fully satisfied by the Samara region of Russia, for which the practical (experimental) part of the research was carried out.

2. Feature generation and vegetation classification

When developing procedures for the feature generation and natural areas classification, researchers face a number of difficulties.

Firstly, the reflectance properties of vegetation in different spectral bands of even one spacecraft can vary greatly in different imaging sessions – they depend on the season, weather, and imaging angle. As a result, the training of vegetation image classification procedures has to be carried out under conditions of significant class instability (variability of the training sample features).

Secondly, the size of training set (the number of pixels of reference polygons within a single image) may be insufficient for the application of sophisticated neural network recognition methods working with high-dimensional feature vectors. Therefore, it is necessary also to consider classification procedures with a small number of parameters for training, as well as to limit the dimensionality of the feature space to avoid the effect of overfitting.

Thirdly, for the practical application of information technology, the speed of processing is important. Given the large size of satellite images, it is advisable to use feature generation and classification algorithms with low computational complexity.

To improve the classification quality, spectral image channels are often supplemented with synthetic components – fields of various features that take into account statistical and/or structural features of the image in the neighborhood of the processed pixel. Each field of synthetic features is usually formed as a result of local processing of one of the image components according to the well-known "sliding window" scheme. Fast recursive algorithms that can efficiently calculate various local image features, such as linear [14] or entropy [15], look promising here. However, the feasibility of using such synthetic components is the subject of further research and is not considered in this article.

Many researchers have confirmed that the use of multi-temporal images (several images during the vegetation season of plants) improves plant recognition because it allows to track the phenological differences between them [16, 17]. We also use a series of images. And the spectral components of the multi-temporal images, corresponding to a pixel with the same coordinates, are concatenated to form a single feature vector. If necessary, the PCA method (principal component analysis) is used to reduce the dimension of the feature space while effectively representing classes in the space of spectral features [18].

Further, the paper will mainly consider the practical implementation of the technology for searching for reference polygons in the steppe territory of the Samara region, because it more closely reflects the accepted monitoring concept. Images from the Sentinel-2 spacecraft were used as remote sensing images. Currently, Sentinel-2 data has practically no competitors among medium-resolution images in terms of availability, image acquisition frequency, number and range of spectral channels.

When searching for reference polygons in the steppe territory of the Samara region, after reducing the dimensionality of spectral features, the feature vector was supplemented with three features of digital elevation model (DEM): elevation, aspect and slope. Relief features play an important role in the formation of certain phytocenoses [4], so the inclusion of these layers has a positive effect on the quality of classification. However, in conditions of a small number of reference polygons, there is no guarantee that all plant communities will be represented on all landforms, so the practical implementation also includes the possibility of regulating the influence of DEM layers on classification (this is discussed in detail in [19]).

A fully connected neural network with two hidden layers was used as a classifier. The output of the network for each considered terrain point is a vector of dimensionality equal to the number of classes, the values of which can be interpreted as the degree of confidence in the belonging of this point to each of the classes. Consequently, the class number will be assigned according to the maximum value of this vector (equal to vector argmaximum).

3. The search of new reference polygons

To identify new sites (candidates for new reference polygons), we propose to use one of two schemes.

The first scheme is more accurate, but requires a rather large amount of information to be processed and analyzed. This scheme is based on the search for areas that reliably retain spectral characteristics inherent to existing reference polygons for several years. In the conducted study, images for three consecutive years (2021-2023) were analyzed for two areas of natural steppe vegetation. Candidates for new reference polygons were selected, most of which were confirmed to belong to identified vegetation class by field visits.

The second scheme, described further in this paper, is designed for urgent analysis in the current vegetation season. As is known, ground-based analysis of natural steppe vegetation should be carried out in the first half of the growing season (in the second half steppe vegetation dries out and distinguishing its species is difficult not only on space images, but also during field survey). Therefore, the search for candidates for new reference polygons is carried out on the basis of remote sensing images obtained by the current moment. This method is less accurate, but it allows to make field visits in the current year without waiting for the end of the vegetation season. The conducted experiments allow estimating the number of images required for vegetation classification and outlining the dates of field surveys in the current year.

It is known that the use of several remote sensing images corresponding to different stages of plant growth increases the accuracy of their classification. However, the issue of necessary and sufficient number of images remains open for each specific task. Modern spacecrafts (in particular, Sentinel-2 used in this work) allow receiving images of the territory with high periodicity (every 2-3 days for Sentinel-2 for the latitude of Samara region), i.e. for 6 months of the growing season in Samara region (April-September) it is theoretically possible to receive quite a significant number of images. On the one hand, the use of a large number of images makes it possible to trace changes in reflectance properties of all plants under consideration, which provides very valuable information for analysis. On the other hand, it increases the computational complexity of the analysis, and may simply be unattainable due to the presence of clouds on the images. In the present work, if alternatives were available, the dates of images were chosen to cover the period of the most dynamic changes of steppe zone grassy plants (April-June) with a frequency of once every two weeks, and once a month for the subsequent period (July-September). The second half of the vegetation season, which is of little information for natural steppe vegetation, may be important for the classification of other vegetation, such as woody vegetation.

This section considers the problem of determining the number of images required to classify natural steppe grassy communities growing on the territory of two protected areas of Samara region. The proposed method can be transferred to other plant communities.

As described in Section 2 of the current work and in [19], to determine the class of natural steppe communities, the channels of multi-temporal remote sensing images were staked together, then the dimensionality of spectral features was reduced using PCA. Three DEM layers (elevation, aspect and slope) were attached to the spectral features and fed to the input of a fully-connected neural network with two hidden layers and the ability to adjust the influence of DEM layers on classification. At the output of this network, for each point we obtain a vector of confidence C, whose values are analogous to the probability that this point belongs to each class (after the softmax activation function). These values allow us not only to determine the preferred class number (as the argmaximum of the C vector), but also to understand how this solution is preferable to other possible solutions.

The research conducted for remote sensing images of 2023 was as follows. We sequentially increased the number of multitemporal images and classified them by a neural network. In order to keep the complexity of the network (number of layers and adjustable parameters) the same each time, the stack of image channels was processed by PCA algorithm (with limitation of the output number of channels). For *each number of images*, several features were calculated based on the classification result (confidence vectors). By analyzing these features, it is possible to select the number of images required to solve the problem.

The following characteristics were analyzed.

1. Classification accuracy on training set ("Acc"). As can be seen (Fig. 2*a*), the classification accuracy increases with increasing the number of images used. However, the percentage of image points included in the training set is small, which is a peculiarity of the considered task. Therefore, we cannot guarantee that the training sample covers the entire diversity of natural plant communities in the protected area. The following two indicators are calculated for the whole territory and provide more information for analysis.
2. For the entire protected area, we calculate the percentage of points for which the value of the maximum component of the confidence vector C is greater than 95 % ("High confidence percent"). That is, what percentage of decisions about belonging to a certain class is made with high confidence. As can be seen in Fig. 2*b*, the value of this criterion first increases with the number of images, reaches a maximum for the number of images equal to four, and then fluctuates. This fluctuation may be related to the fact that natural steppe vegetation dries up starting from mid-July and its type classification from space images becomes difficult. Analysis of vegetation in the first half of the growing season is most informative.
3. The next indicator of classification dynamics is based on the use of the well-known Wald sequential classification algorithm [20], in which the number of features for classification is sequentially increased, and the decision to classify a particular point is made on the basis of comparison of the likelihood ratio with a threshold value. It is important to mention that points, that were classified with less feature number, are not considered further. As an analog of the likelihood ratio value, we use the ratio of the two maximum values of the components of the confidence vector C. Thus, for each number of images r, we can compute the relative number of points that can be classified at this stage $V(r, border)$, where *border* is the likelihood ratio threshold value. And also then calculate the average number of images required for classification $M_V(border)$. Fig. 2*c* shows the cumulative values $V_C(r, border) = \sum_{i=1}^{r} V(i, border)$ for different values of border. The average number of images was 3.37 for *border* = 10 and 2.75 for *border* = 5 (according to Wald algorithm *border* = 19 for errors $p_0 = p_1 = 0.05$). The last column in the chart shows the percentage of points for which no solution was made having available images.

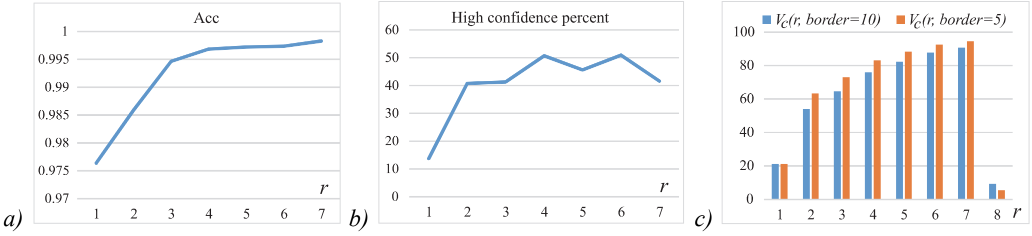


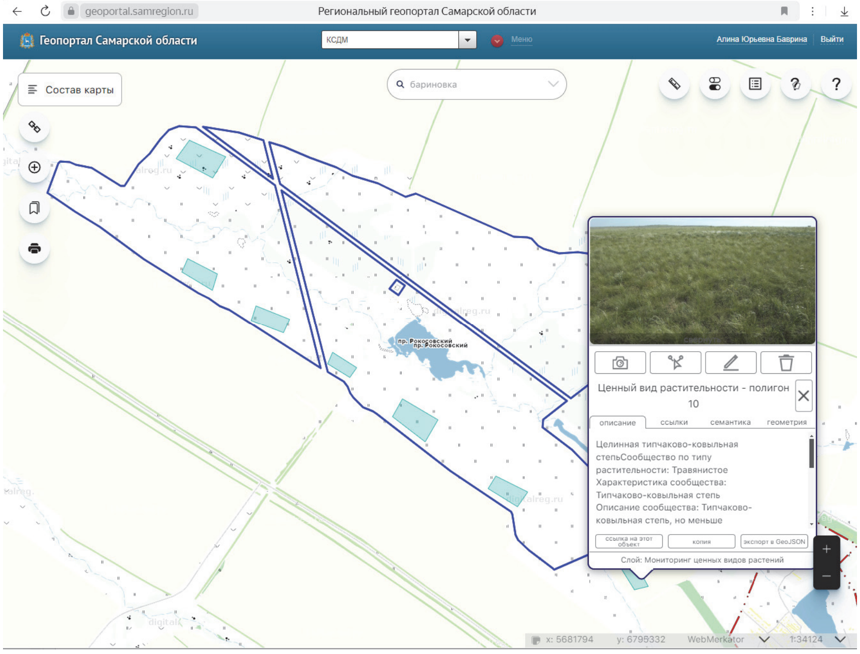
Fig. 2. Analysis of number of images required to solve the problem of steppe vegetation classification. (a) classification accuracy on training set, (b) high confidence percent on whole territory of protected areas, (c) cumulative percent of classified territory points for each image number

Thus, we can conclude that to analyze natural steppe territories in urgent mode it is possible to limit ourselves to three to five remote sensing images acquired during the first period of the growing season. It is worth mentioning that the goal of our project on natural phytocenoses monitoring is not semantic segmentation of the entire territory. Natural communities show variability of reflective properties depending on many factors: precipitation, temperature conditions, and landforms. The goal is to establish a network of reference polygons, and on the basis of these polygons to monitor valuable communities, analyze changes and search for new areas for their study and conservation.

4. Practical results of information technology application

The proposed information technology was successfully tested on the territory of Samara region. Monitoring was carried out using Sentinel-2 images [12, 19], unmanned aerial vehicle [21], high-resolution data from open sources [22].

A database of reference polygons and identified phytocenoses was created, it includes digital map "Plant Monitoring" of the regional geoportal (https://geoportal.samregion.ru/), accumulating data on the boundaries of objects and semantic information about them (Fig. 3). For the seasons of 2023 and 2024, the database was updated with 413 objects of phytocenoses, including 319 objects of valuable plant communities, 4 objects of invasive plants and 90 other plant communities.



Целинная типчаково-ковыльная степьСообщество по типу растительности: Травянистое Характеристика сообщества: Типчаково-ковыльная степь Описание сообщества: Типчаково-ковыльная степь, но меньше

Fig. 3. Interface of regional geoportal with reference polygons

New reference polygons were found for the territory of several steppe protected areas of Samara region using Sentinel-2 images and reference polygons identified in 2018. Most of allocated polygons confirmed their belonging to classified plant communities [19]. Some of these polygons were outside the boundaries of protected area, so it was recommended to expand the protected area (due to the presence of a large number of rare plants). Ground surveys were also conducted in other steppe protected areas [23], the corresponding reference polygons were included in the database, and the list of valuable plant communities, present in the steppe territory of the Samara region, was expanded.

The task of updating the forest inventory data was solved using Krasnosamarskoye forestry as an example [12]. Using Sentinel-2 images and "clean" tree classes as reference polygons, the areas requiring field visits were identified. The field visits confirmed the inconsistency of vegetation parameters with the inventory data.

A number of regions with the presence of the invasive plant Elaeagnus angustifolia were also included in the base of reference polygons [22]. This introduced species has adapted well to the sharp continental climate of the Samara region and causes depression of meadow vegetation, reducing biodiversity. This species is well identified on high and ultra-high resolution images due to specific silver color of leaves. Whether it will be identified on medium resolution images remains to be seen.

An unmanned aerial vehicle (UAV) was used to monitor a rare species of peony (Paeonia tenuifolia) grown in artificial conditions of the Samara Botanical Garden and returned to its natural habitat [21]. UAV images of plants in the Botanical Garden were taken as reference polygons, and then the flowers were searched from the images in a natural environment characterized by complex topography. The high percentage of peony detection significantly reduces the labor-intensive population monitoring required to assess the status of the reintroduced species.

Conclusions

The proposed information technology for regional monitoring of phytocenoses has demonstrated its efficiency and effectiveness when used in the Samara region. Maintenance and constant replenishment of the base of reference polygons allows keeping records of both valuable and invasive plant communities, capturing their characteristics. And the use of remote sensing images ensures effective monitoring, providing reliable and up-to-date information for biodiversity conservation and environmental management activities.

It can be confidently asserted that the technology is applicable to other regions with comparable level of geoinformation support, study and accessibility of phytocenoses located on their territory.

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