Detection and age estimation of burned areas of natural grassy communities in the Samara region using Sentinel-2 data

Alina Bavrina
Image Processing Systems Institute of RAS - Branch of the FSRC "Crystallography and Photonics" RAS;
Samara National Research University
Samara, Russia
bavrina@mail.ru

Lyudmila Kavelenova
Samara National Research University
Samara, Russia
lkavelenova@mail.ru

Oksana Kuzovenko
Samara National Research University
Samara, Russia
stipa4@yandex.ru

Natalya Prokhorova
Samara National Research University
Samara, Russia
natali.prokhorova.55@mail.ru

***Abstract*—An analysis of the environmental and socio-economic aspects associated with the steppe fires – periodically recurring natural and natural-anthropogenic emergencies – shows their high importance as a negative phenomenon for the Russian Federation. The article discusses the possibility of the detection of burned areas and their age estimation based on the calculation of spectral indices between two consecutive Sentinel-2 acquisitions. The study was conducted for the natural grassy communities of the Samara region, for which an increase in fires was observed in 2018. Using up-to-date sources of remote sensing allows to obtain additional data for research and analysis of pyrogenic processes in our region.**

Keywords—Remote Sensing, burned area detection, natural grassy communities, spectral indices

I. Introduction

Landscape fire represents a burning process that is not amenable to control, arising spontaneously and actively spreading in the environment. This phenomenon can occur for natural reasons: as a result of a lightning strike, volcanic eruption, sparks carving, caused by stone blows during a fall. Paleobotanical studies have shown that periodic wildfires are natural for the steppe zone, the pyrogenic factor largely determined the appearance of the modern steppe.

But at present, the most often cause of natural fires is the human factor, manifested in intentional burnings (agricultural burnings), in violation of fire safety measures, in the faults when the extraction and transportation of minerals, forestry and agricultural work, etc. [1]. The increase in the number of dry years intensified the negative consequences of wildland fires in the forest and steppe regions of our country. Since the late 90s of the XX century in our country there has been a sharp increase in the number and scale of fires also due to a reduction in agricultural production, a decrease in cattle grazing, which contributes to the active accumulation of plant rags (associated with the restoration of vegetation) on unused pastures, hays and arable lands [2].

In general, an analysis of publications on this topic shows that the opinions of researchers on the role of the pyrogenic factor can vary significantly. Some authors emphasize the improvement of pasture conditions after fires in the steppe [3], while others, on the contrary, state the degradation of natural grassy phytocenoses. It is noted that an increase in the scale, intensity, and regularity of fires leads to significant disturbances and transformation of steppe ecosystems. The upper layers of the soil burn out, grasses with a shallow root system die, shrubs with a low crown and a surface occurrence of renewal buds suffer significantly, and a seed bank is destroyed. The ratio of different plant groups is changing: natural steppe vegetation is shifting towards weedy species, and rare species are dying [4-7].

The increase in the scale, frequency, and intensity of the steppe fires has led to the growth of researchers' attention to this problem, as well as influenced the expansion of the arsenal of methods and technologies for studying fires causes and consequences in the steppe regions of our country. In addition to traditional ground-based research, modern technologies are increasingly being engaged, in particular, Remote Sensing (in this work only optical sensors are considered).

Currently, the area of Remote Sensing (RS) is quite developed. Many satellites provide data in various spectral ranges and spatial resolution. Some data, both near-real-time and archival, are open for free access, which, undoubtedly, allows the conducting of research at a new qualitative level. Today, as well as over the past many decades, the main operational information about the sources of ignition comes after the analysis of the land surface temperature, obtained from instruments aboard Earth-observing satellites in near-real-time (AVHRR, MODIS, and VIIRS instruments). The most widely used Active Fire product is provided by the FIRMS resource [8] on the base of MODIS and VIIRS instruments. Using these data, the date and approximate fire position can be obtained, however, to estimate the area of burned territory, the values of the spectral brightness coefficients in the visible and near-infrared ranges should be used. Of course, not all fires can be recognized using Active Fire products. Short-lived, low-intensity and small area fires (which steppe fires often are) can be not registered in Active Fire data.

To estimate the burned area, data of medium spatial resolution are widely used. Until recently, these were mainly data from the Landsat program, which has been providing images since 1972 (data in public access are from the later date). With the advent in 2015 of Sentinel-2 data, which have a higher spatial resolution, and most importantly, a shorter revisit period (every 2-3 days), researchers have the ability for more comprehensive analysis of the causes and consequences of fires. The consistency of the Sentinel-2 and Landsat-8 spectral bands provides an opportunity for combined analysis of these data.

Despite the small revisit period, sometimes it is not possible to obtain cloud-free images over a rather long period, and Active Fire data does not contain points within the study area. This work aims not only to detect burned area based on the available Sentinel-2 images but also to obtain an estimation of the "age" of the burn (the number of days that have passed since fire until the observation time) to provide researchers with more complete data for analysis.

The work is organized as follows. The second section provides a brief overview of the methods and algorithms for burned area detection using RS images. The third section is devoted to the description of the used technology for burned area detection and determination of the age of burn, experimental studies of its effectiveness, as well as the analysis of the results. Subjects for further research are in conclusion.

II. Remote Sensing in the study of steppe fires

The works of Russian researchers are focused on the analysis of long-term dynamics of steppe fires, identifying causes and patterns, generation of fire periodicity maps of the study area. Such studies have been performed for the Volgograd, Orenburg, Astrakhan regions, Kalmykia [2, 7, 9, 10]. Predominantly, burned areas detection was carried out in these works manually to ensure the required accuracy. Visual interpretation continues to be used (including for training and validation) since the expert is able to distinguish rather minor colour gradations, take into account texture and contextual information.

In the studies of foreign authors, in addition to traditional visual analysis, data dimensionality reduction, supervised and unsupervised classification, spectral mixture analysis, time series analysis, object-oriented analysis are used [11-13].

Changes in the spectral signatures of vegetation that arise as a result of a fire can be used to determine burned areas [11]. When the vegetation is burned, there is a sharp decrease in the reflection coefficient from the visible to the near-infrared range of the spectrum, and the reflectivity in the short and medium infrared part increases. For this reason, the burned areas are relatively easy to distinguish visually. However, automatic detection is challenging due to the wide range of spectral signatures and spatial heterogeneity, caused by fire conditions, the type of burned vegetation, and environmental conditions.

Spectral indices are widely used for automatic detection of burned areas using remote sensing images due to their conceptual simplicity and computational efficiency [14–16]. Some spectral indices have been developed specifically to detect the effects of fire: BAI, CSI, MIRBI, NBR. As studies show, the NBR and MIRBI indices have the greatest efficiency [14, 16]. In addition to spectral indices, a frequently used tool is the detection of changes in time-consistent images (before and after a fire), as this significantly reduces the errors, caused by spectral similarities between burns and terrain objects, such as water, shadows, dark soil [11].

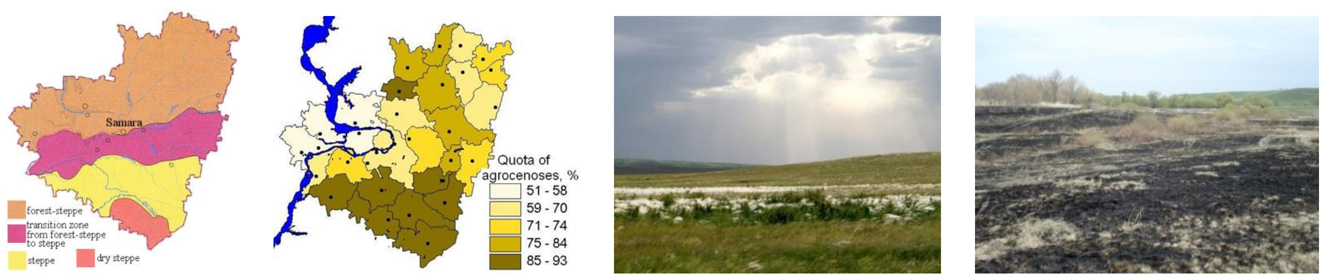
For classification, both classic methods, such as the maximum likelihood classifier and k-nearest means, and relatively modern methods are used: the support vector machines, decision trees, neural networks, random forest [12, 13, 17].

It should be noted that the development of a method that yields good results in the entire diversity of steppe territories is rather difficult, therefore, in recent years, locally-adaptive algorithms that take into account the specifics of the studied region have been used more [12].

The Samara region is characterized by a wide distribution of steppe landscapes (Fig. 1). Despite the significant agricultural load, areas of natural steppe vegetation are quite diverse in steppe species and the representation of rare plant species. Among the works in the Samara region, the work of Ilyina V.N. should be highlighted [4], that presents the theoretical foundations and analysis of the pyrogenic factor of steppe natural ecosystems using ground-based research. The authors are not familiar with the examples of studying steppe fires in the Samara region using Remote Sensing data, so we hope that this work will lay the foundation for more intensive research on this crucial issue in our region.

III. Detection of burned areas using Sentinel-2 data

In this study, when highlighting the area covered by the fire, the authors relied mainly on the work [16], in which a study of small-area fires was conducted using Sentinel-2 data and the Active Fire product of the MODIS spectroradiometer. Burned area detection was performed using a two-stage algorithm. At the first stage, the spectral indices (MIRBI and NBR2) and the NIR channel were compared for two sequential images. Initial burned areas were selected on the basis of fixed thresholds, provided that the Active Fire point was nearby. At the second stage, the values of the differential spectral indices MIRBI and NBR2 for initial burned areas were used to form a probabilistic curve of belonging of an arbitrary pixel to the burned territory.



(a) (b) (c) (d)

Fig. 1. The Nature of the Samara region: (a) terrestrial zones; (b) map of ratio of agrocenoses; (c) fescue-feather grass steppe; (d) steppe fire effects.

TABLE I. CHARACTERISTICS OF THE USED SENTINEL-2 BANDS

Band	Central wave length, nm	Band width, nm	Spatial resolution, m
B8A	865	33	20
B11	1612	142	20
B12	2194	240	20

In the current paper, we apply the idea of using differential spectral indices to highlight the territory covered by the fire. These values are used to train the burn age classifier. Information on the date of the fire (necessary to obtain the age of the burns for the territories from the training pool) is taken from the Active Fire data of the MODIS and VIIRS spectroradiometers.

Table 1 shows the spectral ranges of the Sentinel-2 channels used in this work. When calculating the spectral indices, the B8A channel was used as the NIR (Near-Infra-Red) channel for potential compatibility with Landsat-8 data. In the short-wave-infrared diapason, B11 was used as SSWIR (Short-Wave-Infrared Short reflectance,) and B12 as LSWIR (Short-Wave-Infrared Long reflectance).

In the SWIR region, solar radiation is strongly absorbed by the water content in vegetation or soils. Burning and drying out of the soil after a fire will increase the reflection in the SWIR channel. The NBR index uses the near-infrared (NIR) and shortwave-infrared (LSWIR) spectral regions (ρ is the reflectance in the corresponding spectral range) [18].

$$NBR = \frac{\rho_{NIR} - \rho_{LSWIR}}{\rho_{NIR} + \rho_{LSWIR}}.$$

The NBR2 index is a modification of the NBR index that uses the SSWIR range instead of the NIR range. The use of NBR2 instead of NBR, according to some studies, gives a greater separability of the classes of burnt and unburnt vegetation [19, 16]:

$$NBR2 = \frac{\rho_{SSWIR} - \rho_{LSWIR}}{\rho_{SSWIR} + \rho_{LSWIR}}.$$

The MIRBI index was developed for shrub-savannah vegetation, where NIR wavelengths are less useful due to the dry state of the vegetation during the fire hazard period. The index uses the SSWIR/LSWIR spectral bands and, as the studies described in the literature show, its effectiveness is stable over time for savannah ecosystems [20]:

$$MIRBI = 10\rho_{LSWIR} - 9.8\rho_{SSWIR} + 2.$$

Despite the fact that the MIRBI and NBR2 indices are based on the same bands, their joint use is justified, since they have a different distribution and can reduce commission errors. Using the NIR channel (in addition to indices) allows to take into account some texture information about the earth's surface. In addition, the NIR channel is more useful for detecting burned territories than the channels of the visible range of the spectrum taken together [16].

A. *Using spectral indices for burned areas detection*

This section discusses the validity of using the MIRBI, NBR, and NBR2 spectral indices to burned areas detection.

Three territories within the Protected Area "Mulin Dol" (Samara region, Bolshechernigovsky district) are considered (Fig. 2). Two territories were affected by the fire during the growing season of 2018 (Region1, Region2), the third territory remained untouched (Region3). According to the data of the Active Fire vector layer, the ignition in Region1 occurred on 04.17.2018, in Region2 – 05.03.2018.

Fig. 2. Sentinel-2 snapshot of Protected Area "Mulin Dol" (natural colors, 14.05.2018).

Nine cloud-free images of April-September 2018 were selected for the territory under study. All images were atmosphericly corrected using Sen2Cor package [21]. Fig. 3 shows the dependencies of average values of MIRBI, NBR, NBR2 indices by regions from the date of the survey.

The following conclusions can be drawn from the charts.

- All considered indices react to a fire (a sharp increase in MIRBI index and a decrease in NBR and NBR2 for Region1 and Region2 curves in comparison to Region3).
- The value of MIRBI and NBR2 indices for burned areas differs from unburned territory for a rather long period of time (about 4 months for the surveyed territories).
- Approximately one month after the fire, the values of the indices change quite smoothly (which indicates the restoration of vegetation in this area).
- The NBR index value for burned areas reaches the value for unburned area after about a month (crossin of Region1 and Region2 curves with Region3 curve).

Therefore, any of the indices under consideration can be used for the time-sensitive detection of burned areas. If more than a month has elapsed between the fire and the acquisition date, it is advisable to use the MIRBI and NBR2 indices to detect burns. A month after a fire it is rather difficult to determine the "age" of burned area.

B. *Technology for burned areas detection and age estimation*

The proposed technology for determining of burned areas and their age estimation using remote sensing images can be represented with the following steps.

1. Selection of cloud-free images. Image pre-processing up to level 2 (sen2cor package for Sentinel-2 data) – atmospheric correction.
2. Obtaining images containing the differences of spectral indices (differential spectral indices) and the difference of NIR band. Pairs for which the time interval between surveys does not exceed a month are analyzed.

3. Training set generation. Active fire data are used to obtain information on the age of the burn.
4. Training of the classifier.
5. Application of the classifier to a specific pair of images. Only natural vegetation is considered (using a mask).
6. Post-processing of classification results (median filter).
7. Analysis of the classification results.

C. The study of technology effectivenes

When training the classifier, the territory on the border of the Samara and Orenburg regions was considered (Figure 4), on which natural steppe territories with and without protected status are located. "Active Fire" data of MODIS and VIIRS sensors for the period April-July 2018 were analyzed. The training involved 11 pairs of images, from which the difference spectral indices MIRBI, NBR2 and the difference channel NIR were calculated.

Polygons were outlined in the vicinity of Active Fire points (polygons covered only a fragment of the burn detected in the image). Each polygon corresponded to a certain "age", which was defined as the difference between the date of the later snapshot and the date of Active Fire point. Class labels were formed as follows: 0-5 days (class number is 2), 6-10 days (class 3), 11-20 days (class 4), older than 20 days (class 5). Burns over 30 days old were not considered. In addition, a class of natural vegetation, not affected by fire, was formed (class 1). The multispectral data of various image pairs (difference values of MIRBI, NBR2, and NIR for polygon samples) and the corresponding class labels were docked together; this data was fed to the classifier for training.

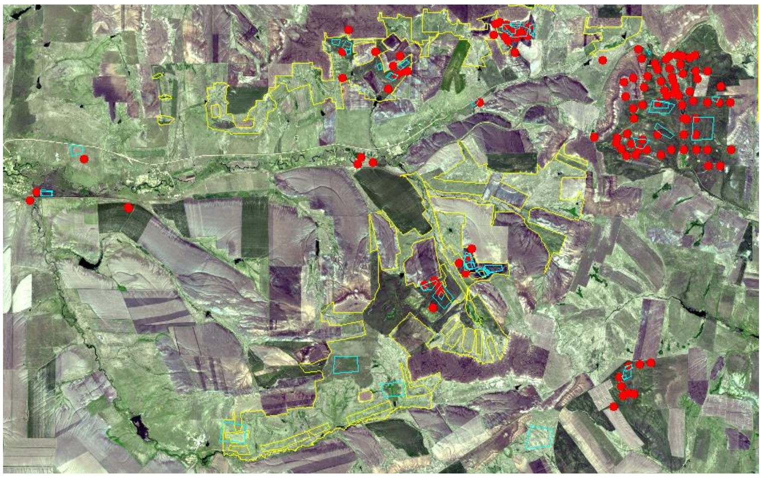


Fig. 3. The territory under investigation (the area is more than 70 000 hectares). Red dots are "Active Fire" points in the investigated period, light blue are polygons of training set, yellow are Protected Areas.

The classification was carried out using the SVM-RBF method [22], implemented in the Visual Studio environment using the DLib library [23]. Since the training sample volume for different classes are different, a restriction on the number of samples of each class was used (a maximum of 7000 samples was taken).

The classification quality was studied using the cross-validation algorithm. The confusion matrix, the probabilities of correct classification by classes, and the average probability of correct classification are presented in Table 2 and Table 3.

TABLE II. CONFUSION MATRIX

Confusion matrix				
0.9917	0	0	0	0.0083
0	**0.9518**	0.0078	0.0404	0
0	0.0106	**0.6773**	0.3115	0.0006
0.0207	0.0191	0.4462	**0.4584**	0.0556
0.1647	0	0.0134	0.1315	**0.6904**

TABLE III. CLASSIFICATION QUALITY BY CROSS-VALIDATION

Class number	Correct classification probabilities	Average probability of correct classification
1	0.9917	
2	0.9518	
3	0.6773	0.7539
4	0.4584	
5	0.6904	

The confusion matrix analysis shows:

- probability of a correct classification of the absence of fire is 0.9917;
- probability of a correct fire detection is 0.9627;
- probability of missing a fire is 0.0373;
- probability of false fire detection is 0.0083.

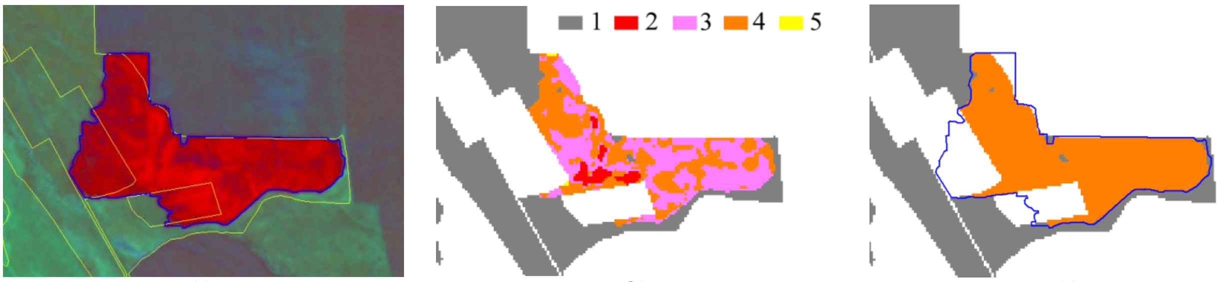
Regarding the age of the fire, a good probability of a correct classification is shown for classes 1 and 2 (lack of burning and "young" burning). Classes 3 and 5 show an acceptable probability of a correct classification. Class 4 samples are approximately equally likely to be classified into both class 4 and class 3. There may be several reasons for this. It is possible that at this age of burning (11-20 days) there is a difference in the rate of recovery of various types of vegetation. It is also likely that this is due to differences in the rate of change of vegetation depending on the growing season (in April-July, vegetation recovers faster than in August-September). From this point of view, the age of burned area can be interpreted as the degree of vegetation recovery after a fire.

Also, experiments on the detection of burns and determination of their age were conducted in the territories considered in Section IIIA (Fig. 5 for Region1, Fig. 6 for Region2). The developed technology for burned areas detection was applied to them. To obtain the territory affected by the fire, the union of classes 2-5 was carried out.

The results were compared with the results of burned areas detection made by a specialist in the field of remote sensing data processing (through visible and infrared channels). Fig. 5a and 6a show the composites from the difference values MIRBI, NBR2, and NIR (features for classification), the territory of Protected Areas is highlighted with a yellow outline (further masking of the natural steppe territory is carried out), the blue outline corresponds to the burned area, identified by the expert. Fig. 5b and 6b show the classification results. Fig. 5c and 6c show the results of burned area detection, obtained by the combining of classes 2-5, while the color of the territory corresponds to the true age of burning.

(a) (b) (c)

Fig. 4. Burned area detection and age estimation for Region1 (true age is 14 days, class 4): (a) the composite of the features for classification, (b) classification results, (c) burned area detection results.



(a) (b) (c)

Fig. 5. Burned area detection and age estimation for Region2 (true age is 11 days, class 4): (a) the composite of the features for classification, (b) classification results, (c) burned area detection results.

For Region1, the burned area allocated by the expert (within the Protected Area) is 701.66 ha, and allocated automatically is 762.24 ha. For Region2, the burned area allocated by the expert (within the Protected Area) is 114.37 ha, and allocated automatically is 112.6 ha. It should be noted that the difference between the areas includes the fraction introduced by the pixels on the perimeter of the contour, which can be assigned to one or another class depending on the rule of rasterization of the vector contour.

This part of the research shows good results of the presented technology for the burned area detection using Sentinel-2 data. The results on burned areas age estimation are consistent with numerical data (mixing of 3 and 4 classes) and can be explained by the difference in the rate of restoration of various types of vegetation and weather conditions. Consideration of these factors should improve the quality of classification and provide a better understanding of the processes occurring in the natural steppe territories.

IV. Conclusion

The protection of valuable natural objects, the study of processes and the control of changes taking place on their territory, the environmental literacy of the population are tasks that a conscious society comes to the importance of despite the instability and economic difficulties. Phenomena that can lead to loosening of the fragile ecological balance must be studied and prevented. For this, it is necessary to join the efforts of various departments and researchers from different fields and integrate diverse data sources.

In this work, world experience and modern data sources are used to obtain the necessary tools for further studying the dynamics of fires in the Samara region. Improving the quality of the technology of burned areas detection and age estimation is possible through the use of information on the types of vegetation accumulated in the database of regionally verified plots described in previous authors works [24, 25]. It is also planned to consider integrated use of Sentinel-2 and Landsat-8 data, as this allows increasing not only the temporal resolution, but also the spatial one [26].

Acknowledgment

This work was supported by the Russian Foundation for Basic Research (18-01-00748 a) and the RF Ministry of Science and Higher Education within the state project of FSRC "Crystallography and Photonics" RAS under agreement 007-GZ/Ch3363/26.

References

[1] L.K. Isaeva, “Ecology of fires, industrial and natural disasters,” M.: Academia GPS MVD Rossii, 2000, 301 p.

[2] V.M. Pavleychik, “Long-term dynamics of natural fires in the steppe regions (on the example of the Orenburg region),” Bulletin of the Orenburg State University, vol. 6, no. 194, pp. 74-80, 2016.

[3] G.N. Lysenko, “Stability of steppe phytocenostructures: thermodynamic aspect,” Materials of the IV International Symposium “Steppes of Northern Eurasia”, pp. 449-451, 2006.

[4] V N. Ilyina, “Pyrogenic impact on vegetation cover,” Samarskaya Luka: problems of regional and global ecology, vol. 20, no. 2, pp. 4-30, 2011.

[5] L.V. Martinova, "Comparative assessment of impact of the pyrogenic factor on the vegetable cover of the steppe zone," Bulletin of KrasGAU, no. 6, pp. 112–119, 2016.

[6] V.G. Koberchinkaya and O.A. Andreeva, "Seasonal productivity of the steppes of the plain Crimea under the influence of the pyrogenic factor," Scientific Notes of V.I. Vernadsky Crimean Federal University. Biology. Chemistry, vol. 3, no. 69, no. 3, pp. 29-43, 2017.

[7] S.S. Shinlarenko, "Assessment of steppe burning dynamics in Astrakhan Region," Current problems in remote sensing of the earth from space, vol. 15, no. 1, pp. 138-146, 2019.

[8] Fire Information for Resource Management System (FIRMS), 2019 [Online]. URL: https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms.

[9] S.S. Shinlarenko and A.N. Berdengalieva, "Analysis of steppe fires long-term dynamics in Volgograd Region," Current problems in remote sensing of the earth from space, vol. 16, no. 2, pp. 98-110, 2019.

[10] M. Dubinin, P. Potapov, A. Lushchekina and V.C. Radeloff, "Reconstructing long time series of burned areas in arid grasslands of southern Russia by satellite remote sensing," Remote Sensing of Environment, vol. 114, pp. 1638-1648, 2010.

[11] J.M.C. Pereira, E. Chuvieco, A. Beaudoin and N. Desbois, "Remote sensing of burned areas: a review," A Review of Remote Sensing Methods for the Study of Large Wildland Fires: Alcala de Henares Spain, pp. 127-184, 1997.

[12] E. Chuvieco, F. Mouillot, G.R. Werf, J.S. Miguel, M. Tanase, N. Koutsias, M. Garcia, M. Yebra, M. Padilla, I. Gitas, A. Heil, T.J. Hawbaker and L. Giglio, "Historical background and current developments for mapping burned area from satellite Earth observation," Remote Sensing of Environment, vol. 225, pp. 45-64, 2019.

[13] R. Meng and F. Zhao, "Remote sensing of fire effects: A review for recent advances in burned area and burn severity mapping," Remote Sensing of Hydrometeorological Hazards, Taylor & Francis Group, vol. 12, pp. 261-281, 2017.

[14] L. Schepers, B. Haest, S. Veraverbeke, T. Spanhove, J. Vanden Borre and R. Goossens, "Burned Area Detection and Burn Severity Assessment of a Heathland Fire in Belgium Using Airborne Imaging Spectroscopy (APEX)," Remote Sensing, vol. 6, no. 3, pp. 1803-1826, 2014.

[15] A.M.S. Smith, N.A. Drake, M.J. Wooster, A.T. Hudak, Z.A. Holden and C.J. Gibbons, "Production of Landsat ETM+ reference imagery of burned areas within Southern African savannahs: comparison of methods and application to MODIS," International Journal of Remote Sensing, vol. 28, no. 12, pp. 2753-2775, 2007.

[16] E. Roteta, A. Bastarrika, M. Padilla, T. Storm and E. Chuvieco, "Development of a Sentinel-2 burned area algorithm: Generation of a small fire database for sub-Saharan Africa," Remote Sensing of Environment, vol. 222, p. 1-17, 2019.

[17] A.V. Kuznetsov and V.V. Myasnikov, "A comparison of algorithms for supervised classification using hyperspectral data," Computer Optics, vol. 38. no. 3, pp. 494-502, 2014, DOI: 10.18287/0134-2452-2014-38-3-494-502.

[18] C.H. Key and N. Benson, "The Normalized Burn Ratio (NBR): A Landsat TM Radiometric Measure of Burn Severity," US Geol. Surv. North. Rocky Mt. Sci. Center, 1999.

[19] M.J. Lopez-Garcia and V. Caselles, "Mapping burns and natural reforestation using Thematic Mapper data," Geocarto International, vol. 6, no. 1, pp. 31-37, 1991.

[20] S. Trigg and S. Flasse, "An evaluation of different bi-spectral spaces for discriminating burned shrub-savannah," Remote Sensing, vol. 22, no. 13, pp. 2641-2647, 2001.

[21] Processor for Sentinel-2 Level 2A product generation and formatting [Online]. URL: http://step.esa.int/main/third-party-plugins-2/sen2cor.

[22] B.E. Boser, I.M. Guyon, V.N. Vapnik, "A Training Algorithm for Optimal Margin Classifiers," Proceedings of the 5th Annual Workshop on Computational Learning Theory (COLT'92), Pittsburgh, pp. 144-152, 1992.

[23] Dlib toolkit with machine learning algorithms and tools [Online]. URL: http://dlib.net.

[24] A. Bavrina, A. Denisova, L. Kavelenova, E. Korchikov, O. Kuzovenko, N. Prokhorova, D. Terentyeva and V. Fedoseev "Some Problems of Regional Reference Plots System for Ground Support of Remote Sensing Materials Processing," Information Technologies in the Research of Biodiversity, Springer Proceedings in Earth and Environmental Sciences, Springer, Cham, pp. 131-143, 2019, DOI: 10.1007/978-3-030-11720-7_18.

[25] A.Y. Bavrina, A.Y. Denisova, L.M. Kavelenova, E.S. Korchikov, O.A. Kuzovenko, Y.V. Makarova, N.V. Prokhorova, D.A. Terentyeva and V.A. Fedoseev, "Natural and revitalized grassy ecosystems as biodiversity refuges: on the abilities of remote sensing for their detection and study," Journal of Physics: Conference Series, vol. 1368, no. 3, 032021, 2019. DOI: 10.1088/1742-6596/1368/3/032021.

[26] A.M. Belov and A.Y. Denisova, "Spectral and spatial super-resolution method for Earth remote sensing image fusion," Computer Optics, vol. 42. no. 5, pp. 855-863, 2018, DOI: 10.18287/2412-6179-2018-42-5-855-863.