ISSN 1029-8940 (Print)
ISSN 2524-230X (Online)
UDC 630*432:630*587
https://doi.org/10.29235/1029-8940-2021-66-3-320-332 Received 15.01.2021

Alexander A. Dvornik[1], Alexander M. Dvornik[2], Roman S. Kurilenko[1], Alesya V. Bardyukova[1], Veronica N. Sehlin[1], Natalia V. Shamal[1], Raisa A. Korol[1]

[1]*Institute of Radiobiology of the National Academy of Sciences of Belarus, Gomel, Republic of Belarus*
[2]*Francisk Skorina Gomel State University, Gomel, Republic of Belarus*

MAPPING OF FOREST FIRE HAZARD DEPENDING ON WEATHER CONDITIONS USING GEOINFORMATION TECHNOLOGIES

Abstract. An important component of forest firefighting strategies is related to the accurate prediction of fire risks. This article describes the development process of special decision support system (ForestFire GIS) – for the analysis of climatic conditions and definition of fire risks in Belarus including radioactively contaminated territory. The application consists of two basic modules: fire danger rating module and module of radionuclides transfer during the fire event. Fire danger rating module uses data on daily temperature, dew point and 24-hour rainfall to calculate weather based fire hazard index (FHI). The program provides recommendations for firefighting officials about efficient wildfires suppression strategy. GIS core (based on the MapWinGIS) performs all basic operations with map layers (scaling, moving, geocoding etc.), load and save changes. The ForestFire GIS was tested for the beginning of fire seasons in Gomel region in Belarus.

Keywords: decision support system, fire hazard, forecasting accuracy, fire management, mapping, radioactive contamination

For citation: Dvornik A. A., Dvornik A. M., Kurilenko R. S., Bardyukova A. V., Sehlin V. N., Shamal N. V., Korol R. A. Mapping of forest fire hazard depending on weather conditions using geoinformation technologies. *Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya biyalagichnykh navuk = Proceedings of the National Academy of Sciences of Belarus. Biological series*, 2021, vol. 66, no. 3, pp. 320–332. https://doi.org/10.29235/1029-8940-2021-66-3-320-332

А. А. Дворник[1], А. М. Дворник[2], Р. С. Куриленко[1], А. В. Бардюкова[1], В. Н. Сеглин[1], Н. В. Шамаль[1], Р. А. Король[1]

[1]*Институт радиобиологии НАН Беларуси, Гомель, Республика Беларусь*
[2]*Гомельский государственный университет им. Ф. Скорины, Гомель, Республика Беларусь*

КАРТИРОВАНИЕ ПОЖАРНОЙ ОПАСНОСТИ ЛЕСОВ В ЗАВИСИМОСТИ ОТ ПОГОДНЫХ УСЛОВИЙ С ИСПОЛЬЗОВАНИЕМ ГЕОИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ

Аннотация. Важный компонент стратегии борьбы с лесными пожарами – точное прогнозирование пожарных рисков. В статье описан процесс разработки специальной системы поддержки принятия решений (ForestFire GIS) для анализа климатических условий и определения пожарных рисков в Беларуси, в том числе на радиоактивно загрязненной территории. Приложение состоит из двух основных модулей: модуля оценки пожарной опасности и модуля переноса радионуклидов при пожаре. Модуль оценки пожарной опасности использует данные о дневной температуре, точке росы и суточных осадках для расчета индекса пожарной опасности на основе погодных условий (FHI). Программа содержит рекомендации для сотрудников пожарных служб по эффективной стратегии тушения пожаров. Ядро *геоинформационных систем* (ГИС) выполняет на основе MapWinGIS все основные операции со слоями карты – масштабирование, перемещение, геокодирование и т. д., загружает и сохраняет изменения. ГИС ForestFire была протестирована на данных начала пожарного сезона в Гомельской области Беларуси.

Ключевые слова: система поддержки принятия решений, пожарная опасность, точность прогнозов, управление пожарами, картографирование, радиоактивное загрязнение

Для цитирования: Картирование пожарной опасности лесов в зависимости от погодных условий с использованием геоинформационных технологий / А. А. Дворник [и др.] // Вес. Нац. акад. навук Беларусі. Сер. біял. навук. – 2021. – Т. 66, № 3. – С. 320–332 (*на англ. яз.*). https://doi.org/10.29235/1029-8940-2021-66-3-320-332

Introduction. Among natural emergencies, forest fires are one of the most harmful disasters. During the last decades, vegetation fires in Eastern and Central Europe has become more common, intensive and less controllable as a consequence of land-use, social and economic changes and coupled with the impacts of global and regional climate changes [1]. Large and severe wildfires are occurring more frequently than in the past and are events that seriously affect human health, environmental security and economic losses [2, 3].

Wildland fires on terrains contaminated by chemicals and radionuclides create new nonstandard risks for firefighters, residents and environment. This issue is of special interest for Belarus because of the radioactive contamination in the south-east region. Resuspension of long-lived radionuclides with smoke aerosols during biomass burning can lead to a secondary radioactive contamination of the neighborhood and to additional internal exposure of people in the area of fire [4].

Since 1986 Belarus has a large forested areas contaminated by technogenic radionuclides. The most contaminated territories (up to 59.2 $MBq \cdot m^{-2}$ of ^{137}Cs in 1986) are located in 30-km zone around the Chernobyl NPP [5]. An important issue for contaminated territories is related to the distribution of ^{241}Am. The activity of this isotope is slowly growing with time through the beta-decay of ^{241}Pu (half-life 14.4 years). Corresponding studies show that ^{241}Am doubled in concentration of the past 20 years in the areas with Pu contamination [6].

According to the regulations on forest management in contaminated territories, all economic activities in the restricted areas are limited (except environmental activities, scientific and experimental work). Due to the absence of preventative cuttings of trees in restricted areas over the last 3 decades, a significant amount of radioactively contaminated organic matter has been accumulated under the forest canopy. Wrong practice to burn fields in spring and summer often leads to the ignition of contaminated forests and to peat fires. Peats in contaminated territories could smolder within the fire season polluting the neighbourhood with radionuclides deposited in fuel materials [7, 8]. On the other hand, ignitions in contaminated areas of the 30-km zone basically depends on weather conditions as they are restricted for humans to enter. The intensity of the fire and the total area burnt down from a fire are mainly determined by fuel load, topography as well as many other physical parameters which is usually difficult to describe within one model [9].

The seasonal nature of the occurrence of fires is strictly related to the weather conditions. In countries with a temperate climate (Belarus, Ukraine, Poland etc.) the fire season begins in the end of March and usually ends in October. Due to climate anomalies, exceptionally many fires occurred in 1996, 1999, 2002, 2006 and 2015 [10–12]. The latest large forest fire on the territory of the Polessie State Radiation-ecological Reserve (PSRER) occurred in 2015 with the total burnt area over 10 000 ha and greater transboundary impact. Although the measures taken to prevent forest fires in contaminated areas, human

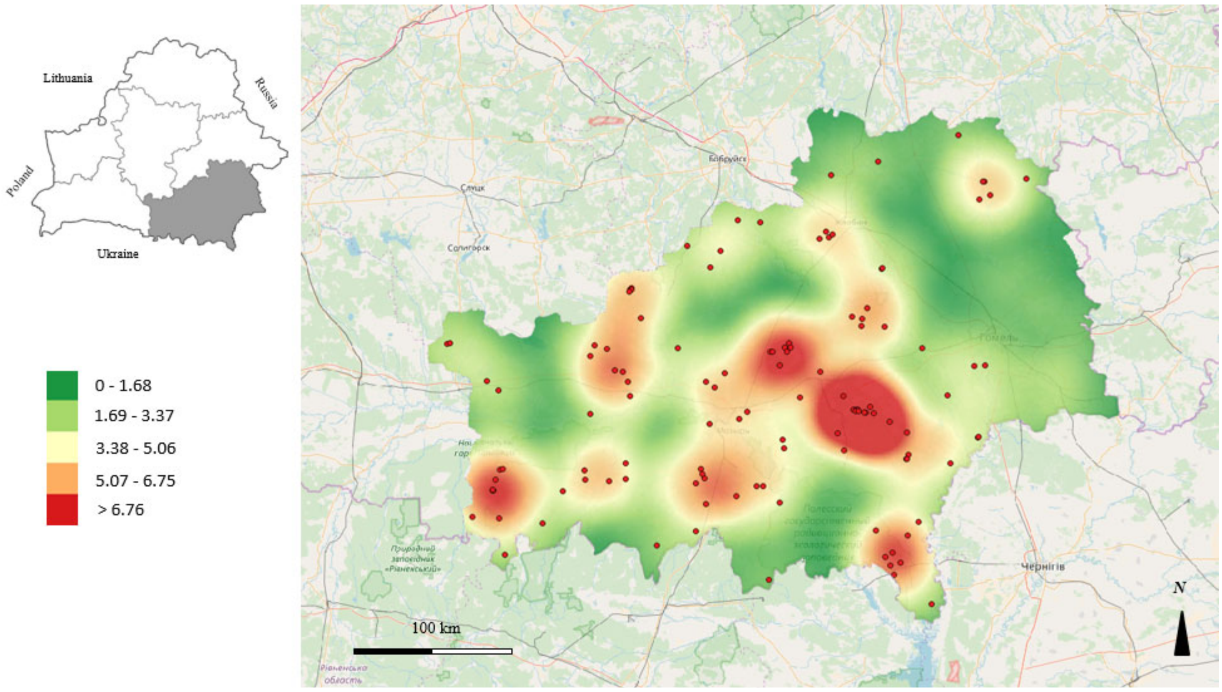

Fig. 1. Map of the ignition point density (number per km^2) in Gomel region (Belarus) in 2018. The ignition point density was calculated using the Point Density tool of QGIS software [13]. The red points indicate the ignition point location

factor remains the main driver of ignition. Belarusian fire statistics show that up to 125 forest fires, leading to burning of areas >220 ha, occurred in Gomel region in 2018, including 9 fire events in hardly accessible areas of PSRER. Fig. 1 highlights the spatial variation of fire event locations and ignition point densities within 2018.

The spatial analysis of fire locations showed that up to 80 % of ignition points are situated near highways and settlements or within a short distance away (a 5-km radius). This is related to the fact that each district has the most frequently visited forest sites.

Fig. 2 shows the relationship between number forest fires and different weather parameters. Moisture and air temperature has significantly less influence on wildfires spreading (Fig. 2, *a*, *b*) than the precipitation level. There is a strong correlation between the number of wildfires and the absence of precipitation ($R^2 = 0.79$, $n = 183$, $p = 0.05$). It should be noted that the summer of 2018 was exceptionally warm and dry in Belarus. Throughout April 2018, there were 27 days with less than 1 mm of rainfall

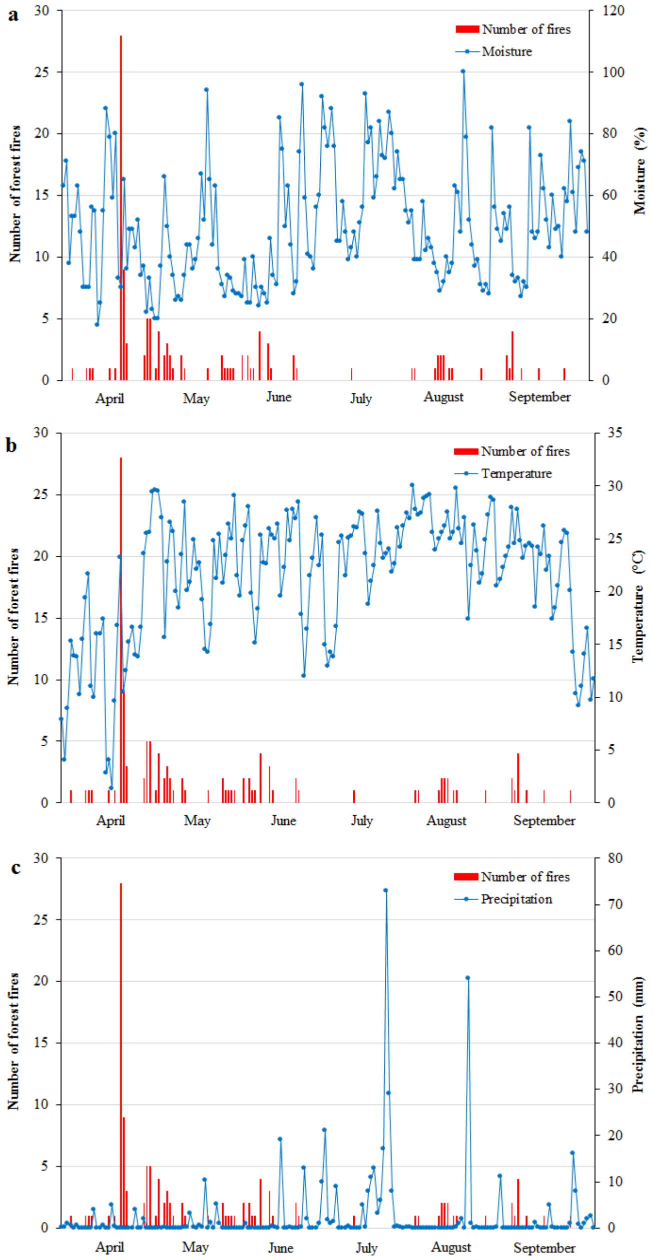

Fig. 2. The relationship between weather parameters (blue dots) and the number of forest fires (red bars) in the Gomel region in 2018 (*a* – moisture; *b* – temperature; *c* – precipitation)

(Fig. 2, *c*). The average daily precipitation in April is 0.6 mm. In May, the amount of rainfall was also very small and did not exceed 0.7 mm. A significant increasing of precipitation occurring in June and July (although less than the average for the same months in the area). The most abundant rainfall came in July, with a maximum of >70 mm. In August and September, the average precipitation level decreased to 2.2 and 1.2 mm per day, respectively.

According to the current administrative structure of regions and districts, state administrations are responsible for overall environmental security and public health. In addition, they are responsible for proper implementation of fire prevention measures, mobilization of fire suppression forces and evacuation of population in case of fire threat to settlements or infrastructure. However, there is a weaknesses related to manual calculations of fire hazard and records, which did not meet the purpose of the quality control since it depended largely on the knowledge and accountability of the staff members involved.

For the above reasons, the selection of forest firefighting strategies based on accurate forecasting of fire risks, in hardly accessible areas of the 30-km zone, has become one of the current and near future priorities for environmental researchers in Belarus. Managing forest fire risks based on reliable information and forecasts on fuel loads, amount of radionuclides flowing out to the atmosphere through burning of contaminated biomass may be done using geographic information systems (GIS) and remote sensing. Such methods are strongly supported by radioecologists, researchers and public authorities [14, 15].

Our study of fire hazard Chernobyl affected regions has been continued in 2018 with the main aim to develop an automated decision supporting system (DSS) for the analysis of the weather conditions and the definition of fire risks in the forestry enterprises of the Gomel region, including radioactively contaminated territories.

Materials and research methods. ***Weather-based fire danger.*** The level of forest fire hazard in the Republic of Belarus is estimated by used a five-graded scale based on the weather conditions, where the fifth degree of fire danger is the highest and the most hazardous (Tab. 1). The weather forecast used in the scale is provided by the "Republican center for hydrometeorology, control of radioactive contamination and environmental monitoring" (Belhydromet), a branch of the Ministry of Environment of Republic of Belarus. This scale is used to estimate fire risks in contaminated areas through calculation of a weather-based fire hazard index (FHI_N, i.e. national index). From year to year, the calculation of fire hazard index begins after the descent of snow cover, and then continues daily until the autumn, when the fire season is over.

T a b l e 1. **Weather-based fire hazard index used in Belarus based on weather conditions**

Total amount of precipitation for 10 days, mm	Fire danger class				
	I (very low)	II (low)	III (moderate)	IV (high)	V (extreme)
	Weather based fire hazard index				
5–15	<130	131–500	501–4000	4001–10 000	>10 000
16–25	<230	231–600	601–4000	4001–10 000	>10 000
>26	<330	331–700	701–4000	4001–10 000	>10 000

Calculation of FHI_N is based on consecutive daily observations of temperature, dew point and 24-hour rainfall in 7 stations (the total number of meteorological stations and posts in Gomel region is 27) [16]. These stations are aimed to collect daily raw data from each post in the region. After processing the results applies to each corresponding administrative district in the region.

The calculation also takes into account the number of days since precipitation (dry days). Days with precipitation amount less than 5.0 mm, are considered to be dry. If precipitation level exceeds 5.0 mm the FHI_N is reset to zero. In this case, to assess the fire-weather danger class a total amount of precipitation for 10 days is used. FHI_N is estimated by following equation [17]:

$$FHI_N = \sum_1^n t(t-r),$$

where t – is the daily noon temperature, °C; r – dew point, °C; n – the amount of dry days.

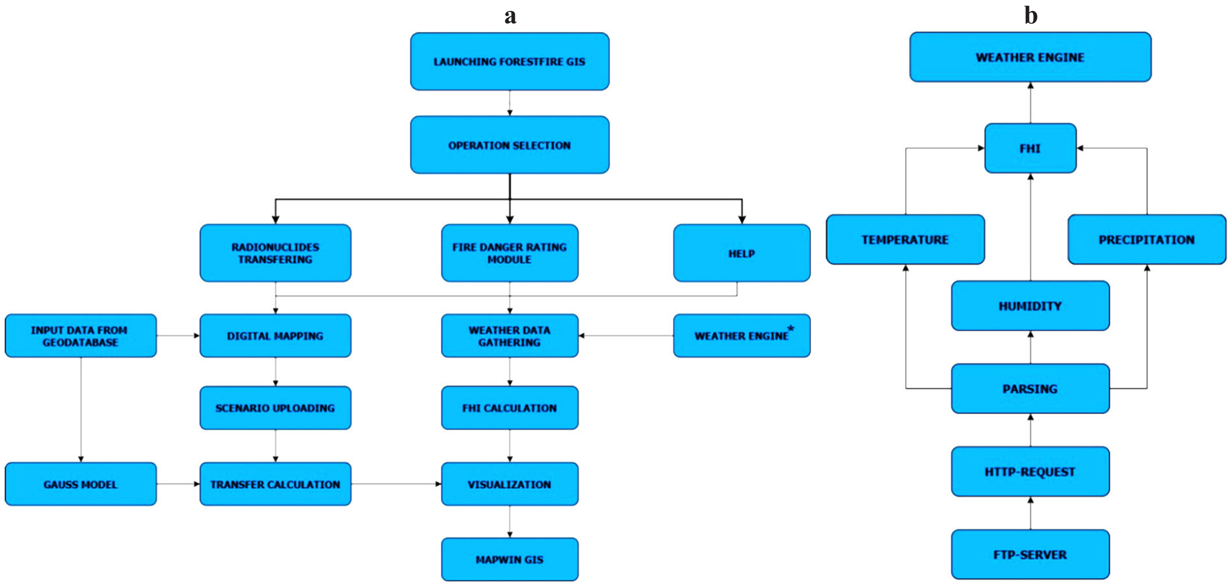

Fig. 3. ForestFire GIS work logic: general structure (*a*) and weather data gathering (*b*)

Based on calculated index, the firefighting strategy are determined with regard to governmental regulations [18]. A similar method of calculation was used in DSS algorithm. The FHI is a crucial parameter for the DSS that provides spatial distribution of fire danger classes by districts.

Software development and data integration. A dedicated digital application, ForestFire GIS (FF GIS), was developed based on the MapWinGIS – a free and open source geographic information system programming ActiveX Control and application programmer interface (API) that can be added to a Windows Form in Visual Basic, C#, Delphi, or other languages that support ActiveX [19]. To build the FF GIS application we used Borland Delphi environment, with the MapWinGIS platform integrated into the FF GIS application. It was an optimal solution to build a new DSS instead of customizing the Quantum GIS platform used Python programming language.

The FF GIS is divided into two main modules that represent to the user different kinds of information and perform different tasks (Fig. 3, *a*). These modules are:

fire danger rating module;

module of radionuclides transfer during the fire event (works for contaminated territories). Within this article, a development and testing of the first module will be reported.

The fire danger rating module incorporate obtaining of weather data (Fig. 3, *b*), geographical data visualization and fire hazard forecasting. Spatial data used by FF GIS stored in a GIS-compatible format – Shapefile (.shp*). The dbf-files contains database with all sets of feature attributes with one record per feature. A detailed description is reported elsewhere [20]. The database is the source of information used to generate, read, and display maps and layers. It contains:

actual data on vegetation type, age of forest stand and fuel load (an average amount of fuel materials for typical forests of Belarusian Polesye, reported by V. V. Usenya [21];

data on density of radioactive contamination by ^{137}Cs (used with module of radionuclides transfer during the fire event);

actual weather data gathering (from public weather service).

For the development of FF GIS, standard software development milestones (e. g. planning, analysis, design, implementation, testing and maintenance) were applied. The details of this development are described below.

Planning. For better understanding the specific needs and overall feasibility of the project, the structure of forest management and decision-making principles were investigated. Furthermore, Belarusian radiation safety requirements for forestry workers in contaminated areas were studied. One of the main objectives of the planning phase was to study the world experience in terms of development and implementation of similar decision supporting systems for wildfires management (AUTO-HAZARD PRO [22], FlamMap by Finney [23] etc.).

Analysis. At the current stage, minimal requirements were defined for the software design. For this purpose, two approaches were used:

interviews with stakeholders;

study of technical documentation for similar systems [24, 25].

The interviews are aimed to find out a professional needs of stakeholders regarding wildfires issues on contaminated territories. Overall, 8 specialists, including forestry and fire managers, radiation protection officers, were interviewed.

Design. The development environment was selected on the basis of usability and possibility for optimal integration of MapWinGIS platform. A general principles of UX/UI design were used on this stge. All functions and operations were described in details within specification, including necessary elements, classes, methods and models.

Implementation. This phase aimed at building a stable version of the program and its individual parts. Particularly, all modules of FF GIS were developed separately. The output of this stage was the implementation of 50 different classes and more than 2000 functions and methods, including a set of graphical interface elements, classes for accessing databases, HTTP syntactical analyzer etc.

The raw data required for the application is obtained from different data sources. For example, weather information may be obtained from public weather service using HTTP-requests. The source data for digital maps is obtained from Gomel forestry FTP-servers. Vector layers were created using georeferencer GDAL plugin in the QGIS platform. Each layer corresponds to real geographical coordinates of forestry objects presented in WGS 84/Pseudo-Mercator EPSG: 3857 projection. Custom maps superimposed on the OpenStreetMaps layer – basic layer worked under the Open Database License.

The module for radionuclides transfer assessment is based on the analysis of climatic, environmental and historical data obtained from continuous datasets in Belarus since 2005 (not described within this article). It also includes field data on fuel load and the distribution of long-lived radionuclides under the forest canopy [26]. All data are stored in the database. The output data incorporate volume activity concentration of ^{137}Cs in the air and activity of fallouts due to resuspension after fires on different distance from the source. Upon discovering a high risk of ignition in contaminated territories user might switch to radionuclides transfer module. It can compute the radiation consequences of wildfires using 1 from 4 available scenarios. To confirm the validity of calculated parameters a field data is required. The main output of this phase was a beta-version for testing.

Testing. This stage included individual and inter-module tests, GUI (graphical user interface) tests, common working tests and data validation. More specifically, tests were performed through the following activities: testing of beta-version of service for calculating atmospheric transfer; testing of beta-version for weather based fire danger rating service and corresponding program interface. As a result, some bugs were identified and corrected.

An official data provided by authorities (FHI_N) remain relevant for the day when prognosis was made. An advantage of FF GIS is the possibility to make prediction up to 5 days. Therefore, a national index FHI performed by Belhydromet is an important source to validate calculations made by FF GIS and assist in prediction of the future fire situation.

An analysis of observed and predicted values was performed by using methods of parametric and non-parametric statistics. The difference between groups was tested using the Manne–Whitney *U*-test (independent samples) and two-sample *t*-test with the same variance. Data are presented as median, range and mean ± standard deviation values. To identify one or more outliers, the ROUT method was applied.

Software application. A stable version of the FF GIS provides the following services: cartographic, weather engine, atmospheric transfer of radionuclides and secondary contamination forecasting, forecasting of forest fires hazard based on weather conditions.

The MapWinGIS-core of the application is responsible for the implementation of GIS related functions i.e. mapping, management of map layers, visualizing styles for formatting graphical elements etc. Map data sets used by FF GIS consist of three basic layers (boundaries, forestry, labels). One extra layer highlighting the density of ^{137}Cs contamination, included to maps working with a module for atmospheric transfer of radionuclides.

In order to calculate FHI for a current day, the application use retrospective data of weather conditions. The “weather engine” is an independent subprogram aimed at continuous gathering weather information (Fig. 3). While working in real time the “weather engine” collects available information on daily temperature, amount of precipitation and air humidity using HTTP-requests. The information gathered is stored in a database in “.dbf” file format, which can be used by FF GIS. Through an appropriate interface, users may choose the forecasting length (up to 10 days).

After the FHI calculation, it is possible to generate predicted fire danger maps. The FHI can be calculated both for a single forestry (selected by the user in the list box) as well as for a whole region. During routine operation, 7 meteorological stations collect relevant data from nearby territories. The FF GIS

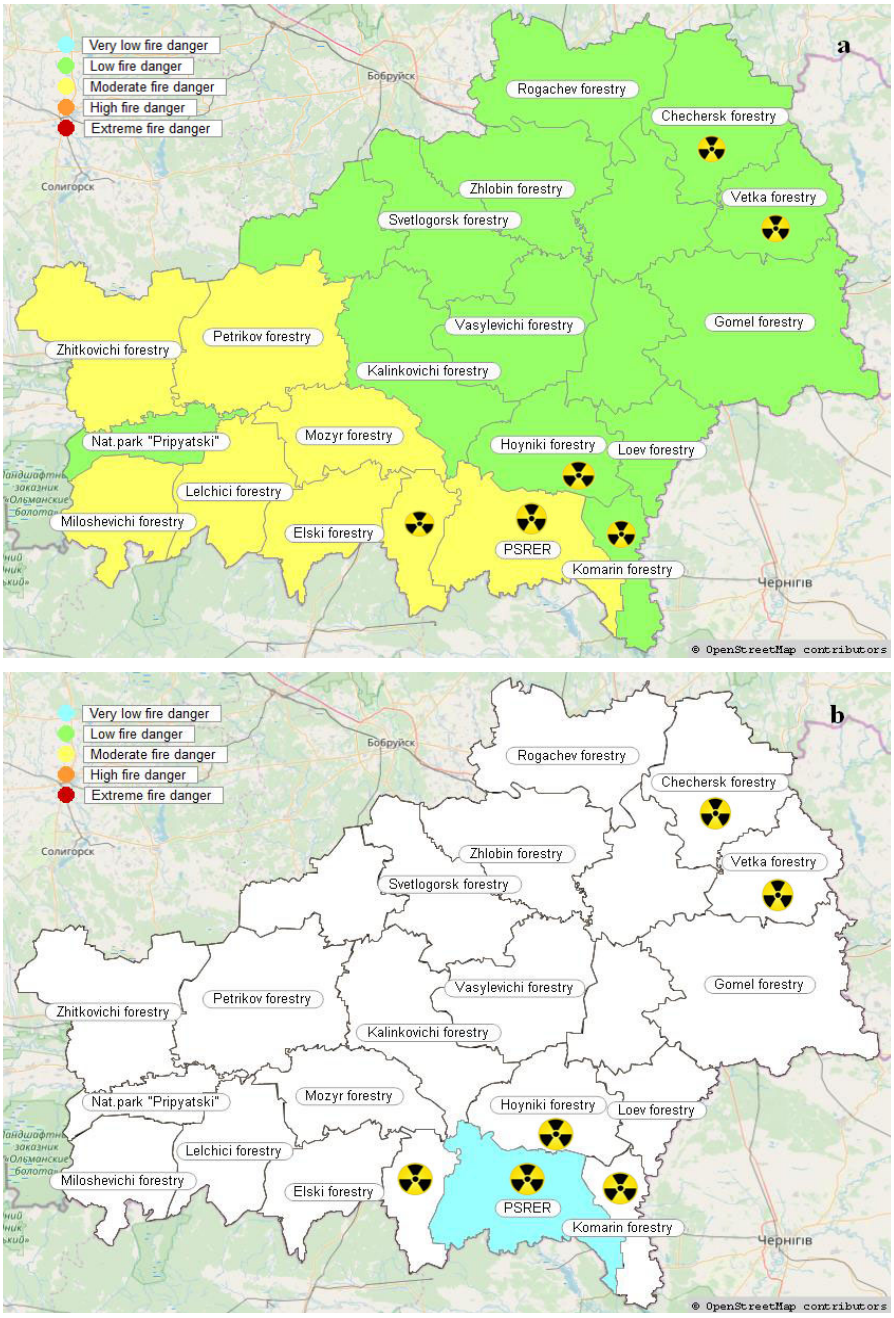

Fig. 4. An example of fire hazard maps created by application for Gomel region (*a*) and for single forestry (*b*). Districts with radiation contamination are marked with radiation hazard symbol

compute FHI for all districts in the region. Some forestries incorporate two administrative districts. In this case, the application takes the maximum FHI value. Thus, the application might create two kinds of maps depends on user choice (Fig. 4).

Fig. 4 shows that each fire danger class represents by its own color. Along with the FHI calculation, guidance for stakeholders is given with accordance to the regulations of efficient suppression strategy for wildfires [18]. More specifically, in the case of full absence of fires, ground and single air patrolling are carried out in a recreational facilities and forest areas with low fire probability. On the territories of radioactive contamination and beyond, a daily air dosimetric survey is carrying out. Emergency preparedness also includes information work with the locals through mass media. If the highest level of fire danger (IV–V fire danger class) is reached, entry to forest areas is prohibited.

***Evaluation of wildfire danger*.** The accuracy in the forecasting of FF GIS is highly depends on the prediction length selected by user and spatiotemporal accuracy of weather parameters forecasts. The results calculated by the program were compared with the official data provided by Belhydromet. The results of comparison are presented in Fig. 5.

April monthly data of FHI_N calculation in six observation points was taken for comparison. For “Zhitkovichi” observation point, predicted values of FHI were approximately 45 % higher than official data. For the remaining locations a predicted values were slightly lower than official data. A comparison reveals a good agreement between data ($t_d < t_{st}$, $p = 0.05$). The results of comparison of observed and predicted FHI values are presented in Tab. 2.

T a b l e 2. **The statistical parameters of data validation**

Parameter	Observation point					
	Gomel	Zhlobyn	October	Brahin	Mozyr	Zhitkovichi
MR_{FHI}^{*}	0.81	0.81	1.18	0.92	0.61	1.55
$SEMR^{**}$	0.06	1.02	0.09	0.15	0.09	0.30
df	22	24	20	20	24	23
t-test ($p < 0.05$)	0.78	0.53	0.6	0.85	0.85	0.36
U-test ($p < 0.05$)	65	69	50	70	73	56
Significantly different	No	No	No	No	No	No

N o t e. * – mean ratio between observed and predicted FHI values; ** – standard error of mean ratio.

The data shows no significant difference between observed and predicted FHI values (values for the Mann–Whitney *U*-test are much higher than table values for corresponding samples with the level of significance $p = 0.05$). The observed-to-predicted ratio is narrowing despite the values from “Mozyr” and “Zhitkovichi” observation points.

Forecasting accuracies varying from 50 to 98 %. The verification shows that the optimal period for forecasts is 3 days with an accuracy up to 95 %, as compared to official data. However, in some cases the accuracy remained high even during the 5 day of forecast. The reason for the deviation, as compared to the official data, for longer forecast periods is not yet determined. Apparently, the more stable weather conditions might provide more accurate forecasting.

The forecasts were also validated from COPERNICUS European Forest Fire Information System (EFFIS) observations. Due to lack of conformity between calculating methods in Europe and Belarus, a comparison of fire danger classes was made. The forecasts might be performed daily, with 5-day predictions. As shown in Fig. 6 the maps of forecasted fire danger level created by EFFIS are in a good agreement with ones created by FF GIS.

Some areas on the FIS GIS maps have a higher fire hazard level than the EFFIS maps. On April 12, some districts show a moderate level of fire danger, while on European maps the moderate level is forecasted beyond the region. The situation has changed on April 24 in most of the Gomel region, except two districts, a moderate level of fire hazard is determined (Fig. 6, *b*). On the other hand, EFFIS maps indicate a moderate level of fire danger only for eastern part of the region (Fig. 6, *a*). It should be noted

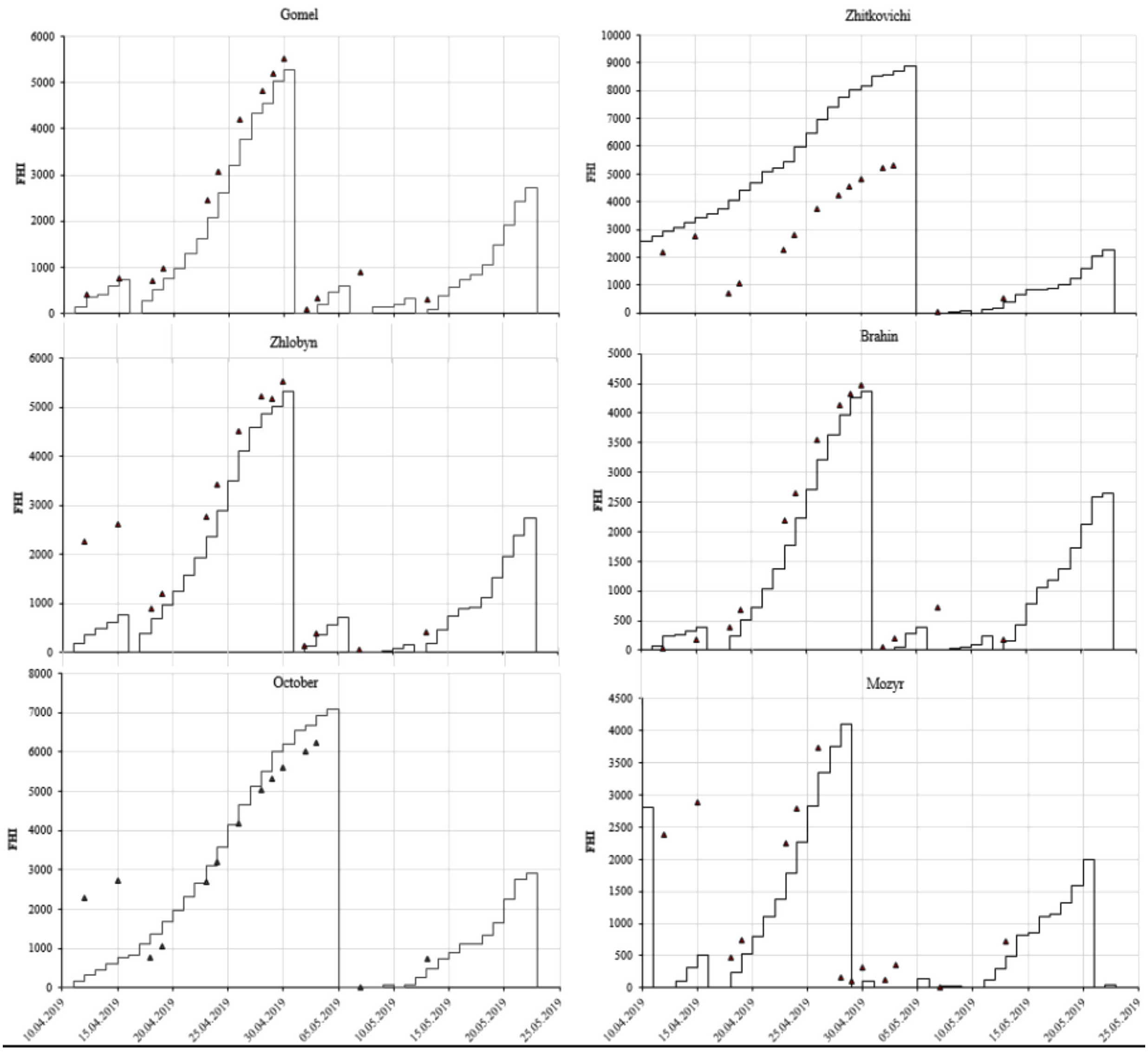

Fig. 5. Comparison of forecasted FHI values with official data. On the graphs: lines highlights FHI values predicted by FF GIS, points represent official data (FHI_N)

that maps created by FF GIS have differences in assigned color code, caused by reduced number of classes.

Results and its discussion. The main output of this work is a modern tool for forest fire risk management, that could be useful not only in contaminated forests but for whole regions. In comparison with other similar systems [22, 23], FF GIS has many significant differences. One of the most important is the special emphasis on radiological consequences of wildland fires. The DSS is providing next services: cartographic, predicting atmospheric transfer of radionuclides and secondary contamination (including transboundary effects), predicting exposure doses for participants of firefighting. The main milestone of implementation is development for Belarus a scientific radiological and firefighting background, base of firefighting knowledge, models and specific thematic maps and system of coordination between forestries and administrative units.

Among the main problems in effective forest fires risk management in Belarus it is important to mention:

lack of reliable and timely spatial information about location of forests with highest fire risk (digital maps for fuel load, infrastructure analysis etc.) and effective data transfer between forestries and smaller administrative units;

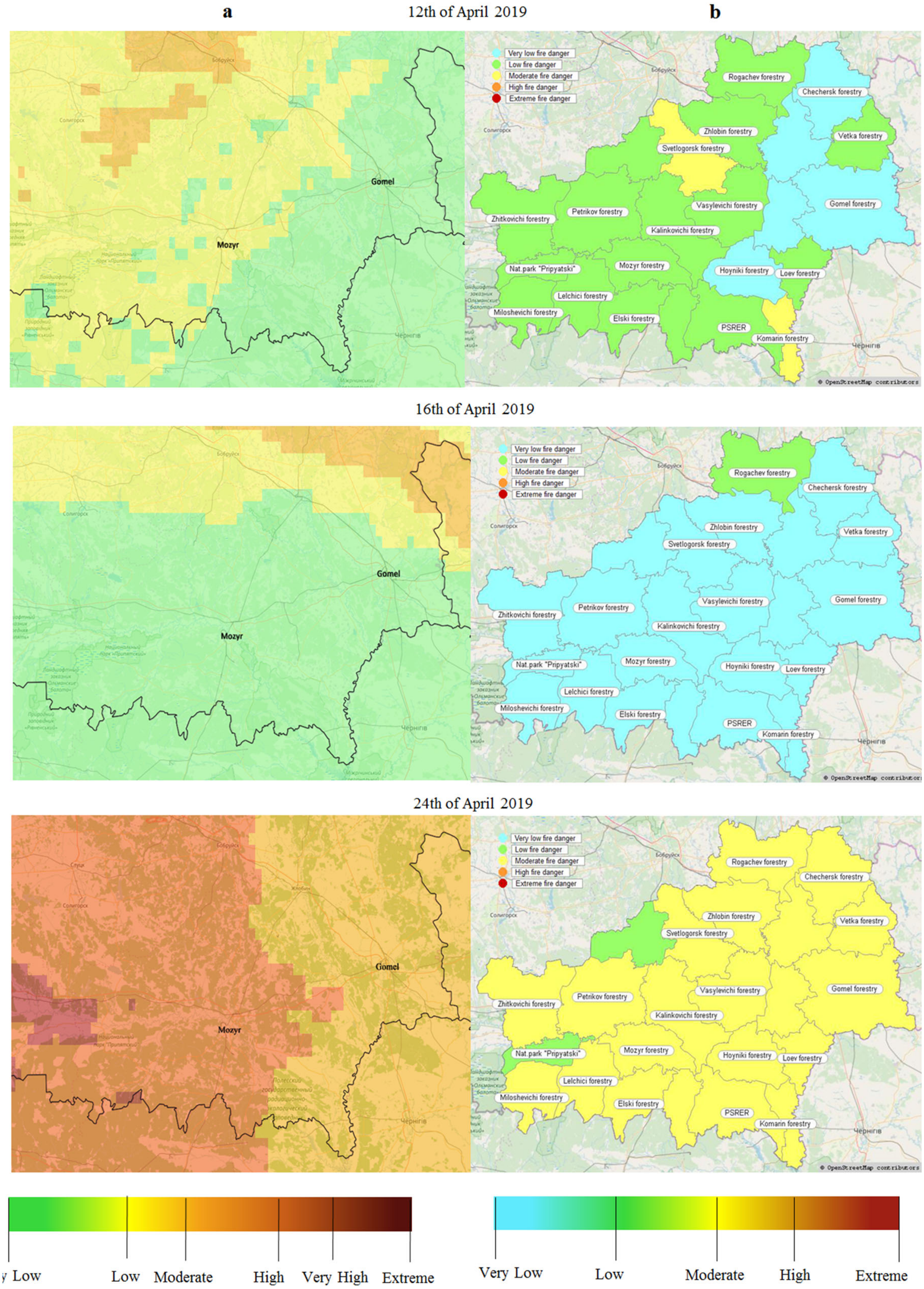

Fig. 6. Comparison of daily maps of forecasted fire danger level from EFFIS (*a*) and FF GIS (*b*). The source of meteorological forecast data is the European Centre for Medium-Range Weather Forecast (ECMWF) with 8 km resolution

absence of prediction scenarios of effective doses for firefighters and emitted amount of long-lived radionuclides during the ignition;

lack of reliable information among local communities on environmental consequences of forest fires including radiological impact;

lack of information transparency for local authorities, stakeholders and decision makers.

Launching the DSS on the territory of Gomel region will give an advantage over the national warning system. The main benefit is to fulfil a five-day prediction daily, thereby improving emergency preparedness and response to wildfire events. An additional module for analysis of radionuclides transfer – a feature that distinguishes FF GIS from systems with similar functionality.

In order to further improve and expand the existing functionality of FF GIS it is important to continue to investigating and compare with other similar decision support systems and the world experience in developing and implementation processes. Currently, the FF GIS software provide users with wide range possibilities:

to work with the forest fires parameters based on database;

forecasting of environmental consequences of forest fires in radioactively contaminated territories (emitted amount of radionuclides, secondary contamination of territories);

calculation of FHI using weather data downloaded from FTP-servers;

coloring elements of the vector layer in accordance with requirements [18].

Conclusion. The aim is to further develop the DSS to improve the acquisition of timely information on physical and radiological forest fire risks in contaminated territories, emergency preparedness of firefighting services and optimization of the early warning system for fires. During this year's fire season, Gomel State Production Forestry Association provides pilot-testing and adoption of the system.

Within the dissemination phase, we aim at involving all crucial stakeholders. The main target groups are:

public authorities of the territories contaminated by radionuclides;

forest and land managers, public agencies and organizations responsible for fire planning and suppression.

The outputs of this work are the first steps in adoption of automated forecasting system of forest fires and its consequences in Belarus. The DSS allows to highlight the benefits of using IT and GIS technology in wildland fires prevention.

Acknowledgements. Materials were presented at the 7th International on the study of nuclear radiation in various fields of research on the Study of Nuclear Radiation in Various Fields of Research (RAD 2019) held in Herceg Novi, Montenegro, in the period from June 10 to June 14, 2019. The authors would specifically like to thank Mr. Dmitriy Yatchenko from Gomel State Production Forestry Association for its invaluable contribution in testing the ForestFire GIS software and support on spatial analysis.

The work was conducted under the project GR_20190137 "The investigation of the dynamics of radioecological and weather indicators during forest fires and the development of a multifunctional decision support system on prevention of fires in the contaminated by radionuclides territories" with the support of the State Program for Scientific Research of the Republic of Belarus.

Благодарности. Материалы были представлены на 7-й Международной конференции по изучению ядерного излучения в различных областях исследований (RAD 2019), проходившей в Герцег-Нови, Черногория, в период с 10 по 14 июня 2019 г. Авторы выражают особую благодарность г-ну Дмитрию Ятченко из Гомельского государственного производственного лесохозяйственного объединения за неоценимый вклад в тестирование программного обеспечения ForestFire GIS и поддержку пространственного анализа.

Работа проводилась в рамках проекта GR_20190137 «Исследование динамики радиоэкологических и погодных показателей при лесных пожарах и разработка многофункциональной системы поддержки принятия решений по предотвращению пожаров на загрязненных радионуклидами территориях» при поддержке Государственной программы для научных исследований Республики Беларусь.

References

1. Mitsopoulos I., Mallinis G., Zibtsev S., Yavuz M., Saglam B., Kucuk O., Bogomolov V., Borsuk A., Zaimes G. An integrated approach for mapping fire suppression difficulty in three different ecosystems of Eastern Europe. *Journal of Spatial Science*, 2016, no. 62, no. 1, pp. 139–155. https://doi.org/10.1080/14498596.2016.1169952

2. Hysa A., Baskaya F. A. T. GIS based method for indexing the broad-leaved forest surfaces by their wildfire ignition probability and wildfire spreading capacity. *Modeling Earth Systems and Environ*, 2019, vol. 5, no. 1, pp. 71–84. https://doi.org/10.1007/s40808-018-0519-9

3. Alcasena F. J., Salis M., Ager A. A., Castell R., Vega-García C. Assessing wildland fire risk transmission to communities in northern Spain. *Forests*, 2017, vol. 8, no. 2, p. 30. https://doi.org/10.3390/f8020030

4. Kashparov V. A., Lundin S. M., Kadygrib A. M., Protsak V. P., Levtchuk S. E., Yoschenko V. I., Kashpur V. A., Talerko N. M. Forestres in the territory contaminated as a result of the Chernobyl accident: radioactive aerosol resuspension and exposure of fire-fighters. *Journal of Environmental Radioactivity*, 2000, vol. 51, no. 3, pp. 281–298. https://doi.org/10.1016/s0265-931x(00)00082-5

5. Izrael J. A., Bogdevich I. M. (eds.). *Atlas of Contemporary and Forecasting Aspects of the Consequences of the Chernobyl NPP Accident on the Affected Territories in Russia and Belarus.* Minsk, Belkartografiya Publ., Moscow, Fund "Ionosphere" NIA-nature, 2009 (in Russian).

6. Knatko V. A., Asimova V. D., Yanush A. E., Golikov Yu. N., Ivashkevich I. I., Kouzmina L. A., Bondar Yu. I. A prognostic estimation of the area contaminated with alpha-emitting transuranium isotopes in Belarus following the Chernobyl accident. *Journal of Environmental Radioactivity*, 2005, vol. 83, no. 1, pp. 49–59. https://doi.org/10.1016/j.jenvrad.2004.07.005

7. Ager A. A., Lasko R., Myroniuk V., Zibtsev S., Day M. A., Usenia U., Bogomolov V., Kovalets I., Evers C. R. The wildfire problem in areas contaminated by the Chernobyl disaster. *Science of the Total Environment*, 2019, vol. 696, p. 133954. https://doi.org/10.1016/j.scitotenv.2019.133954

8. Kashparov V., Zhurba M., Zibtsev S., Mironyuk V., Kireev S. Evaluation of the expected doses of fire brigades at the Chornobyl exclusion zone in April 2015. *Nuclear Physics and Atomic Energy*, 2015, vol. 16, no. 4, pp. 399–407. https://doi.org/10.15407/jnpae2015.04.399

9. Keane R. E., Burgan R., Wagtendonk J. V. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire*, 2001, vol. 10, no. 4, pp. 301–319. https://doi.org/10.1071/wf01028

10. Zibtsev S. V., Goldammer J. G., Robinson S., Borsuk O. A. Fires in nuclear forests: silent threats to the environment and human security. *Unasylva*, 2015, vol. 66, no. 1–2, pp. 40–51.

11. Evangeliou N., Zibtsev S., Myroniuk V., Zhurba M., Hamburger T., Stohl A., Balkanski Y., Paugam R., Mousseau T. A., Møller A. P., Kireev S. I. Resuspension and atmospheric transport of radionuclides due to wildfires near the Chernobyl Nuclear Power Plant in 2015: an impact assessment. *Scientific Reports*, 2016, vol. 6, no. 1, pp. 26062–26075. https://doi.org/10.1038/srep26062

12. Dvornik A. A., Klementeva E. A., Dvornik A. M. Assessment of ^{137}Cs contamination of combustion products and air pollution during the forest fires in zones of radioactive contamination. *Radioprotection*, 2017, vol. 52, no. 1, pp. 29–36. https://doi.org/10.1051/radiopro/2016085

13. *QGIS Development Team, 2019. QGIS Geographic Information System. Open Source Geospatial Foundation Project.* Available at: http://qgis.osgeo.org (accessed 19 June 2019).

14. Huesca M., Litago J., Merino-de-Miguel S., Cicuendez-López-Ocaña V., Palacios-Orueta A. Modeling and forecasting MODIS-based Fire Potential Index on a pixel basis using time series models. *International Journal of Applied Earth Observation and Geoinformation*, 2014, vol. 26, pp. 363–376. https://doi.org/10.1016/j.jag.2013.09.003

15. Evangeliou N., Hamburger T., Talerko N., Zibtsev S., Bondar Y., Stohl A., Balkanski Y., Mousseau T. A., Møller A. P. Reconstructing the Chernobyl Nuclear Power Plant (CNPP) accident 30 years after. A unique database of air concentration and deposition measurements over Europe. *Environmental Pollution*, 2016, vol. 216, pp. 408–418. https://doi.org/10.1016/j.envpol.2016.05.030

16. Drozdovitch V., Zhukova O., Germenchuk M., Khrutchinsky A., Kukhta T., Luckyanov N. [et al.]. Database of meteorological and radiation measurements made in Belarus during the first three months following the Chernobyl accident. *Journal of Environmental Radioactivity*, 2013, vol. 116, pp. 84–92. https://doi.org/10.1016/j.jenvrad.2012.09.010

17. Usenya V. V., Gordei N. V., Klimchik G. Ya., Mukhurov L. I. Method for determining the risk of fire forest under weather on the territory of Belarus. *Trudy Belorusskogo gosudarstvennogo tekhnologicheskogo universiteta* [*Proceedings of the Belarusian State Technological University*], 2015, no. 1, pp. 103–106 (in Russian).

18. *STB Emergency safety. Forest fires monitoring and forecasting.* Minsk, State Committee for Standardization of the Republic of Belarus, 2003. 20 p. (in Russian).

19. Ames D. P. *MapWinGIS reference manual: a function guide for the free MapWindow GIS ActiveX map component.* Idaho Falls, Idaho State University, 2012. 194 p.

20. *ESRI Shapefile Technical Description. An ESRI White Paper*. New York, Environmental Systems Research Institute, 1998. 34 p.

21. Usenya V. V. *Forest fires, consequences and suppression.* Gomel, Forest Institute of NAS of Belarus, 2002. 206 p. (in Russian).

22. Kalabokidis K., Xanthopoulos G., Moore P., Caballero D., Kallos G., Llorens J., Roussou O., Vasilakos C. Decision support system for forest fire protection in the Euro-Mediterranean region. *European Journal of Forest Research*, 2012, vol. 131, no. 3, pp. 597–608. https://doi.org/10.1007/s10342-011-0534-0

23. Finney M. *An overview of FlamMap modeling capabilities. Fuels Management – How to measure success.* Conference Proceedings. USDA, Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-P-41, 2006, pp. 213–219.

24. *Advance EFFIS Report on Forest Fires in Europe, Middle East and North Africa 2018.* Luxembourg, Publications Office, EUR 29722 EN.

25. Stratton R. D. Guidance on spatial wildland fire analysis: models, tools, and techniques. *General Technical Report RMRS-GTR-183*, 2006.

26. Dvornik A. A., Dvornik A. M., Korol R. A., Shamal N. V., Gaponenko S. O., Bardyukova A. V. Potential threat to human health during forest fires in the Belarusian exclusion zone. *Aerosol Science and Technology*, 2018, vol. 52, no. 8, pp. 923–932. https://doi.org/10.1080/02786826.2018.1482408

Information about the authors

Alexander A. Dvornik – Ph. D. (Biol.), Researcher. Institute of Radiobiology of the National Academy of Sciences of Belarus (4, Fedyuninski Str., 246007, Gomel, Republic of Belarus). E-mail: aadvornik@yandex.ru

Alexander M. Dvornik – D. Sc. (Biol.), Professor. Francisk Skorina Gomel State University (104, Sovetskaya Str., 246019, Gomel, Republic of Belarus). E-mail: advornik@gsu.by

Roman S. Kurilenko – Junior Researcher. Institute of Radiobiology of the National Academy of Sciences of Belarus (4, Fedyuninski Str., 246007, Gomel, Republic of Belarus). E-mail: kr.socialmail@gmail.com

Alesya V. Bardyukova – Junior Researcher. Institute of Radiobiology of the National Academy of Sciences of Belarus (4, Fedyuninski Str., 246007, Gomel, Republic of Belarus). E-mail: alesya.bardyukova@mail.ru

Veronica N. Sehlin – Junior Researcher. Institute of Radiobiology of the National Academy of Sciences of Belarus (4, Fedyuninski Str., 246007, Gomel, Republic of Belarus). E-mail: seglinv@mail.ru

Natalia V. Shamal – Senior Researcher. Institute of Radiobiology of the National Academy of Sciences of Belarus (4, Fedyuninski Str., 246007, Gomel, Republic of Belarus). E-mail: namahasha@rambler.ru

Raisa A. Korol – Researcher. Institute of Radiobiology of the National Academy of Sciences of Belarus (4, Fedyuninski Str., 246007, Gomel, Republic of Belarus). E-mail: raisa-korol@mail.ru

Информация об авторах

Дворник Александр Александрович – канд. биол. наук, науч. сотрудник. Институт радиобиологии НАН Беларуси (ул. Федюнинского, 4, 246000, г. Гомель, Республика Беларусь). E-mail: aadvornik@yandex.ru

Дворник Александр Михайлович – д-р биол. наук, профессор. Гомельский государственный университет им. Ф. Скорины (ул. Советская, 104, 246019, г. Гомель, Республика Беларусь). E-mail: advornik@gsu.by

Куриленко Роман Сергеевич – мл. науч. сотрудник. Институт радиобиологии НАН Беларуси (ул. Федюнинского, 4, 246007, г. Гомель, Республика Беларусь). E-mail: kr.socialmail@gmail.com

Бардюкова Алеся Владимировна – мл. науч. сотрудник. Институт радиобиологии НАН Беларуси (ул. Федюнинского, 4, 246007, г. Гомель, Республика Беларусь). E-mail: alesya.bardyukova@mail.ru

Сеглин Вероника Николаевна – мл. науч. сотрудник. Институт радиобиологии НАН Беларуси (ул. Федюнинского, 4, 246007, г. Гомель, Республика Беларусь). E-mail: seglinv@mail.ru

Шамаль Наталья Владимировна – ст. науч. сотрудник. Институт радиобиологии НАН Беларуси (ул. Федюнинского, 4, 246007, г. Гомель, Республика Беларусь). E-mail: namahasha@rambler.ru

Король Раиса Александровна – науч. сотрудник. Институт радиобиологии НАН Беларуси (ул. Федюнинского, 4, 246007, г. Гомель, Республика Беларусь). E-mail: raisa-korol@mail.ru