The dynamics of forest ground fires in the Saratov region

O A Ivchenko, A V Tyutin, M A Kozachenko and K E Pankin
Federal State Budget Education Institution of Higher Education “Saratov State Agrarian University named after N.I. Vavilov”, 1, Teatralnaya sq., Saratov, 410012 Russian Federation, Saratov
E-mail: texmexium@mail.ru

Abstract. Forest fires are inevitable, as they have pyrological properties, which in turn are associated with weather conditions. Forest fire has a dynamics, i.e. the rate of its spreading under weather conditions and will continue until all available forest fuels are burn out or will extinguished. An important component of forecasting forest fire situations is the assessment of the dynamics of a forest fire, which makes it possible to assess the risk of its spread across the territory. The rate of spread of a forest fire is calculated from the ratio of the increment of area to time. Nevertheless, to obtain an accurate estimate, it is necessary to know the time of its occurrence, which is impossible in practical terms, since in case of careless handling of fire, they are usually not fixed for a while, and in case of deliberate arson, it is difficult to find and interrogate the arsonists. For solving this task, a mathematical model was created that makes it possible to calculate the average rate of development of a forest fire based on the rate of development of a fire (increase in the length of the edge of a forest fire over time) during its extinguishing, as well as the rate of extinguishing a fire. An assumption was made about the additive nature of the rate of increase in the length of the edge and the rate of quenching. Average rate of ground wild fire spread and the estimated time of its occurrence were calculated. The rate of spread of ground wild fire are compared with the data on the wind speed in the study area and the value of the complex indicator of fire danger. It was shown that forest fires spread only when the 3rd class of wild fire conditions is established according to weather, and the wind rate affects the dynamics of a ground wild fire only up to a 10 m s$^{-1}$. 

1. Introduction
A forest fire is a special type of natural emergency defined as the uncontrolled spread of flames across a natural landscape. Living nature is in direct interaction with abiotic weather factors, which only create prerequisites for the emergence and development of forest fires. Therefore, forest fires do not occur on their own, their causes come to the forests outside 93-95% of fires are detected later as a result of human activity, and 5-7% are discharges of atmospheric electricity (lightning) [1-3].

Regardless of the causes, a forest fire has a place and time of its occurrence. The combustion process depends of different external factors. Firstly, the presence of forest fuels, their quantity, humidity, uniformity of distribution over the territory. “Nature abhors a vacuum” is one of the most important nature law, manifesting itself in the world of plant organisms in such a way that plants inhabit even the most minimally suitable territories [4]. Secondly, the presence of an oxidizing agent that supports combustion - atmospheric oxygen. Thirdly, the type of terrain also plays a mail role in the spread of a fire in natural landscape - on average, a fire spreads on a slope three times faster than down a slope [5-8].
Forest fire has the dynamics which reflects rate of spread in the natural landscape. The fastest wild fires are crown wild fires, stable ground fires have a minimum rate and in the middle are runaway ground fires, and [1-3]. The rate of spread of a forest fire depends on the strength of external factors. A fire will definitely spread faster the higher the wind speed and the higher the natural fire danger in the area.

If a forest fire spreads throughout the territory, then the conditions for its spread are favorable, however, the dynamics of the fire may undergo changes - changing conditions lead to a change in the rate of fire spread [9]. In connection with the foregoing, the purpose of this work was to identify an estimate of the spread rate of forest ground fires, as well as the influence of wind speed and a comprehensive indicator of fire hazard according to weather conditions on the rate of their spread on the example of the Saratov region.

2. Materials and methods
For the study, data on forest fires in the most forest-rich regions of the Saratov region (Balashovsky, Krasnoarmeisky and Saratov) were involved. Fire extinguishing cards were collected and processed to determine the time of fire detection, its area at the time of detection, information about the time of fire localization and area at the time of localization for the period 2015-2018. To identify the influence of external factors on the forest fire spread rate, information was used on weather conditions and a wild fire index (WFI), calculated from the moisture content of the ground cover in the study area during the onset and development of a forest fire. Weather information was taken from the weather database of the Federal State Budgetary Institution “Privolzhsky Department for Hydrometeorology and Environmental Monitoring”, and WFI were provided by the Forestry Department of the Ministry of Natural Resources and Ecology of the Saratov Region. The approximation equations for the experimental values of the dependence of the GF edge length on time were calculated using the linear least squares method in the Microsoft Excel program included in the Microsoft Office package.

3. Results
The most forested areas of the Saratov region were chosen as objects of study. It is known that the Saratov region is located on the border of the forest and the steppe and has only 7% of the territory covered with forests [10-11]. Almost all large forests are located in the Right-bank part of the Saratov region.

Since the forests in the Saratov region perform mainly an ecological and agricultural function, they are of both natural and artificial origin. Hardwood forests are predominantly of natural origin; conifers - artificially created forests. In the studied forest areas of the Saratov region, oak prevails, while in the forests of the Krasnoarmeisky, Balashovsky and Saratov regions there is a significant proportion of pine forests [12-15]. It is clear that fires in coniferous forests occur more intensely than in deciduous ones, which is associated with the peculiarities of forest fuels formed by coniferous and deciduous tree species [1–3].

To identify the influence of external factors on the rate of spread of a forest fire, the following method was used. The fact is that the time and place of a forest fire is established very approximately when investigating the causes of a fire after it is extinguished. It is not possible to use such information to identify the dynamics of a forest fire due to the low accuracy of the initial data and the unknown time of the start of the fire. Nevertheless, it is possible to calculate the average fire propagation speed based on information about the time of fire detection \( t_{wf} \), the area of the fire at the time of detection \( S_{wf} \), the area of the fire at the end of the localization \( S_{lf} \). The most convenient way to quantify the GF is to use not the values of the fire area, but the value of the length of its edge, because It is on her that firefighters exert their influence when extinguishing. It is possible to calculate the length of the GF edge based on the area according to [7]

To formulate a mathematical model for calculating the dynamics of a forest ground fire (GF), the following prerequisites and assumptions were used: (1) the conditions for the propagation of GF remain unchanged both during its free development and during extinguishing; (2) in the event of an
GF, it is not the area that is extinguished, but the edge of the forest fire; (3) GF spreading does not stop at the beginning of its extinguishing (the opposite can be observed only at very small values of the GF area, in this case, forest firefighters can attack the fire along the entire length of its edge); (4) at the time of the start of fire extinguishing, the length of the extinguished edge is equal to zero, i.e. \(l_t=0\); (5) by the moment of localization of the fire, the length of the extinguished edge is equal to the total length of the edge of the GF, \(l_w=l_f\); (6) Knowing the start and end times of GF extinguishing, as well as the corresponding indicators of the area and length of the edge, it is possible to determine only the average speed indicators, and the coefficient at the argument indicates the rate of development (extinguishing) of the fire edge \((\text{m} \cdot \text{min}^{-1})\). Using all of the above, we can conclude that at the beginning of the quenching of the GF edge, its increase decreases exactly as much as the length of the quenched edge increases. This is obvious, because the extinguished section of the GF edge is no longer able to participate in the transfer of flame to the following sections of the terrain filled with forest fuels. Thus, a set of three points appears that characterizes the development of GF and the process of its quenching. By connecting them (figure 1) with straight lines, it is possible to calculate, using the least squares method, the parameters of linear equations relating the length of the edge of the ground fire and the fire spread time.

\[
y = 0.6537x + 48.506
\]

\[
y = 7.1145x - 2988.1
\]

\[
y = 0.6537x + 48.506
\]

\[
y = 7.76x - 2936.2
\]

\[
y = 7.1145x - 2988.1
\]

Figure 1. Wild ground fire spread and localization scheme.

The use of linear dependencies in assessing the dynamics of the development and extinguishing of forest fires is a common practice [5–7], which makes it possible to calculate the rate of development and extinguishment from known initial and final points. The resulting linear equations of the form \(y=ax+b\) contain an important component which is the coefficient \(a\), the physical meaning is the quantitative relationship between the GF edge length and the time (hour, minute, etc.) of the fire development. In turn, the value of the coefficient \(b\) does not matter much, because expresses the impossible values of the length of the bottom fire edge - has negative values.

Analyzing the equations obtained, it can be determined that the average rate of GF edge growth (spread) is 1.26 m/min \((V_{wfs})\), while the same parameter for quenching is 7.72 m/min \((V_{lf})\). After 50 minutes, the fire was localized, i.e. the length of the edge of the GF was equal to the length of the edge extinguished by forest firefighters. Based on this, we can conclude that the rate of GF development in the absence of its quenching would be \(V_{wfs}=V_{wfs}+V_{lf}\). Thus, the initial rate of fire spread (an increase in
the length of the fire line) under these conditions will be about 9 m/min. Using the obtained speed value, it is possible to calculate the free development time of the fire, which is 323/9 = 36 min. Thus, the GF started around 6.20-6.25 am on August 27, 2018.

The dynamics of GF was revealed only on the basis of data obtained for forest areas with a predominance of pine and oak, to compare the spread rates of GF in coniferous and deciduous forests. The obtained values of the GF dynamics were compared with the data on the weather and the value of the WFI and data on the type of fire and type of forest. The results obtained are presented in table 1.

### Table 1. The dynamics data of wild fires and weather conditions in Balashovsky, Krasnoarmeisky, and Saratovsky districts of Saratov Region in 2015-2018 years.

| Data          | Forest type | Type of wild fire | V_{wf}, m/min | V_{wind}, m/s | RFDI | DFFD |
|---------------|-------------|-------------------|---------------|---------------|------|------|
| 29.04.2015(B) | P(37)       | GLI, GMI          | 7.3           | 2.8           | 3120 | 3    |
| 10.05.2018(B) | P(48)       | G                 | 9.9           | 5.5           | 5666 | 4    |
| 11.06.2018(B) | P(50)       | G                 | 5.3           | 1.4           | 7902 | 4    |
| 12.06.2018(B) | P(80)       | GMI               | 10.8          | 2.1           | 8315 | 4    |
| 13.06.2018(B) | P(80)       | GHI               | 8.4           | 2.1           | 8394 | 4    |
| 26.08.2015(K) | P(35)       | GR                | 4.7           | 2.1 (15)      | 12713| 5    |
| 19.09.2015(S) | P           | GMI               | 4.6           | 4.0 (20)      | 15771| 5    |
| 11.04.2016(B) | P(50-60)    | GMI               | 15.0          | 3.8           | 1526 | 3    |
| 23.08.2017(B) | P           | GHI               | 1.1           | 2.7 (10)      | 15196| 5    |
| 07.09.2018(B) | P(40)       | GMI               | 12.9          | 2.0           | 26068| 5    |
| 16.09.2018(B) | P30         | GMI               | 8.2           | 2.8           | 31337| 5    |
| 27.08.2018(S) | P35         | GMI               | 7.8           | 1             | 24420| 5    |
|               | Coniferous forests (Pinus sylvestris L., 1753) |               |               |               |      |      |
| 02.07.2015(K) | O(76)       | GMI               | 16.0          | 3.3 (15)      | 7000 | 4    |
| 02.07.2015(K) | O(96)       | GMI               | 43.2          | 3.3 (15)      | 7000 | 4    |
| 07.08.2015(K) | O(65-96)    | GLI               | 3.1           | 2.3           | 12382| 5    |
| 09.08.2015(K) | O(40)       | GMI               | 14.3          | 8             | 13264| 5    |
| 09.08.2015(K) | O(40)       | GMI               | 7.1           | 8             | 13264| 5    |
| 13.08.2015(K) | O(90)       | GMI               | 6.4           | 8 (20)        | 15478| 5    |
| 14.08.2015(K) | O(90)       | GMI               | 18.4          | 6 (20)        | 16737| 5    |
| 14.08.2015(K) | O(70)       | GMI               | 14.3          | 6 (20)        | 16737| 5    |
| 14.08.2015(K) | O(80)       | GMI               | 26.5          | 6 (20)        | 16737| 5    |
| 15.08.2015(K) | O(82)       | GMI               | 26.2          | 4 (20)        | 14993| 5    |
| 15.08.2015(K) | O(60)       | GMI               | 61.1          | 4 (20)        | 14993| 5    |
| 15.08.2015(K) | O(60)       | GMI               | 16.6          | 4 (20)        | 14993| 5    |
| 14.10.2015(K) | O(50-70)    | GLI, GR           | 4.7           | 6             | 132  | 1    |
| 19.09.2015(S) | O           | GMI               | 16.2          | 4 (20)        | 15484| 5    |
| 19.09.2015(S) | O           | GMI               | 16.5          | 4 (20)        | 15484| 5    |
| 22.09.2015(S) | O           | GHI               | 18.8          | 2 (8)         | 17961| 5    |
| 23.09.2015(S) | O(60)       | GHI               | 5.1           | 2             | 18833| 5    |
| 24.08.2016(K) | O(88-98)    | GLI               | 1.2           | 3 (20)        | 17477| 5    |
| 26.08.2016(K) | O(80)       | GMI               | 2.6           | 2 (10)        | 18390| 5    |
| 21.09.2017(S) | O(70)       | GMI               | 12.8          | 2 (15)        | 12985| 5    |
| 30.04.2018(S) | O(40)       | GMI               | 110.6         | 3             | 587  | 2    |
| 14.08.2018(K) | O(80)       | GMI               | 1.1           | 2 (10)        | 7877 | 4    |
| 11.09.2018(K) | O(80-100)   | GMI               | 23.8          | 3 (15)        | 22592| 5    |
| 03.09.2018(S) | O(60)       | GMI               | 6.1           | 2             | 28425| 5    |

Note: (B) is Balashovsky district, (K) is Krasnoarmeisky district, (S) is Saratovsky district, G is ground wild fire; GR is runaway ground fire; GLI is low intensity ground fire, GMI is middle intensity ground fire, GHI is high intensity ground fire, O(age) is English Oak, S(age) is Pinus Silvestris, V_{wind} (gusty wind rate) is a rate of wind, RFDI is Russian fire danger index, DFFD is degree of forest fire danger conditions.
4. Discussion

The analysis of the presented data shows, firstly, the uneven occurrence of forest fires in the study areas, both in place and in time of their occurrence. With modern forest management and preventive measures, the occurrence of a forest fire is the exception rather than the rule. However, it is surprising that during the study period there is an increase in the number of forest fires, as well as an increasing number of cases of intentional burning of forest areas. Secondly, forest fires in the Balashovsky district occur both in the first (April-May) and in the second (June-September) fire parts of wild fire season. At the same time, forest fires in the Krasnoarmeisky and Saratov regions occur mainly in the second fire part of fire season (June-September). The reason for this is in the nature of the forests - in the Balashovsky district there are forests which has a predominance of pine, and in Krasnoarmeisky and Saratovsk have with a predominance of oak. Deciduous forests prefer more humid habitats; in the first half of the fire hazard season (FHS), conditions for the emergence of medium and high intensity ground fires are not yet formed here.

Analysis of the results presented in table 1 shows that it is difficult to identify an unambiguous picture of the influence of external conditions on the dynamics of wild fires, however, on average, in pine forests, the rate of spread of WGF is higher than in deciduous forests. The observed isolated cases of violation of this trend are simply a superposition of the conditions in which wild fires spreads. The high wild fire spread rate in deciduous forests under certain conditions can be explained by the structure of the FCM layer in deciduous forests, which is looser and less compact compared to the layer of fallen needles. In addition, the lower tier of oak forests is more populated with herbaceous plants, which increases the mass of fossil fuels per unit area of the forest surface, the combustion of which occurs in the same way as the combustion of detritus.

In general, the wind rate leads to an increase in the rate of development of the GF at comparable values of the WFI. It is known that the influence of wind on the development of the GF is observed only at the border of the forest (the edge). The fact is that the forests in the Saratov region have a special structure, i.e. do not have a large extent and have a significant perimeter.

The WFI determined by the moisture content of the ground cover, has a greater influence on the rate of spread of GF. At low values of RFDI, even with an increase in wind speed, the dynamics of GF decreases. Nevertheless, an increase in the rate of development of GF with an increase in RFDI is observed both in deciduous and coniferous forests, which is natural, because drier fuels burn with more heat, which contributes to the efficient distribution of GF.

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Analysis of the results are presented in table 1 shows that it is difficult to identify an unambiguous picture of the influence of external conditions on the dynamics of GF, however, on average, in pine forests, the rate of spread of GF is higher than in deciduous forests. The observed isolated cases of violation of this trend are simply a superposition of the conditions in which GF develops and spreads. The high rate of spread of GF in deciduous forests under certain conditions can be explained by the structure of the forest fuels layer in deciduous forests, which is looser and less compact compared to the layer of fallen needles. In addition, the lower tier of oak forests is more populated with herbaceous
plants, which increases the mass of fossil fuels per unit area of the forest surface, the combustion of which occurs in the same way as the combustion of detritus.

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The complex indicator of fire danger according to weather conditions, determined by the moisture content of the ground cover, has a greater influence on the rate of spread of GF. At low values of RFDI, even with an increase in wind speed, the dynamics of GF decreases. Nevertheless, an increase in the rate of development of GF with an increase in RFDI is observed both in deciduous and coniferous forests, which is natural, because drier fuels burn with more heat, which contributes to the efficient distribution of GF.

5. Conclusion
As a result of this work shows that the occurrence and development of forest fires in the Balashovsky, Krasnoarmeysky and Saratov districts of the Saratov region were analyzed. It is shown that forest fires in the Balashovsky district are observed both in the first (April-May) and in the second half (July-September) of the fire season in forests, with a predominance of pine. In the Krasnoarmeysky and Saratov districts, fires are observed in the second fire-dangerous period - these are areas with a predominance of oak. Based on a comparison of data on the spread of forest fires during their extinguishing and an assessment of the extinguishing rate, a model was created and substantiated for estimating the average spread rate of a forest ground fire. An estimate of the average rate of spread of GF for coniferous forests with a predominance of pine and oak has been carried out. It has been established that, other things being equal, the dynamics of a forest ground fire in coniferous forests (Pinus sylvestris L., 1753) is higher than that in deciduous forests (Quercus robur L., 1753). An increase in wind speed leads to an increase in the rate of GF propagation both in deciduous and coniferous forests, which is associated with the large length of the forest edge, where the influence of wind is the highest. The complex indicator of fire danger according to weather conditions, calculated based on the moisture content of the forest fuels, has a greater influence on the dynamics of a forest fire than wind rate.

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