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Methods of Assessing Efficiency of Wildfire Monitoring Systems Functioning.

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ABSTRACT

This article considers the process of detecting forest fires as a non-stationary variable intensity Poisson stream. A formula has been developed for determining the probability of fire detection within specified time from the beginning of fire outbreak. Equations for calculating the probability of forest fire detection by several monitoring tools are presented. Absolute and relative indicators for assessing efficiency of forest fire monitoring systems functioning from the point of view of timeliness of detection are proposed. Equations for calculation are presented.

Keywords: forest fires, monitoring, efficiency, detection probability.

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A wide use of various technical tools for monitoring and detecting forest fires [18, 19] today makes it necessary to introduce quantitative methods for assessing their effectiveness [13, 14]. The quantitative characteristic of detection tools effectiveness is related to assessing forest fire detection probability within certain time. The search should be regarded as a random process, the progress and the outcome of which depend on several random factors. Let us consider the search as a random Markovian process [1]. A Markov process is a process in which the future state of the system is determined by its present state, and does not depend on its state in the past.

In considering random Markov processes with discrete states, the concept of "flow of events" is introduced. Flow of events is a sequence of homogeneous events following each other at random moments [2]. In respect to the search process, flow of events is a sequence of detections of the searched object by observers. In the search theory, such a flow is called flow of detections.

The flow of detections has the following properties:

1. Absence of aftereffects: the number of detections that fall into this period does not depend on the number of detections in other periods that do not overlap with it;
2. Ordinariness: the probability of two detections falling into an elementary interval of time is negligible, as compared to the probability of one detection falling into it. This property means that detections of the object occur one by one, rather than in pairs, threes, etc.

A flow of events with the properties of absence aftereffect and ordinariness, which is not stationary (probability of a detection in time period *t* depends on its duration, and does not depend on the location of the period on the time axis) is called a non-stationary Poisson flow.

The method of calculating the probability of forest fire detection with one monitoring tool via search intensity

Let's derive a Poisson distribution formula in respect to the search. Let us determine, being based on the properties of the Poisson search described above, probability P_m of obtaining exactly the specified number of detections *m* during search time t_{srch} .

Let's introduce the concept of flow of detections. Intensity of flow of detections γ is the average number of detections per unit of time. For a non-stationary Poisson flow, search intensity is a variable, time-dependent value (1):

$$\gamma = \gamma(t) \qquad (1)$$

Let's divide the search time into *n* equal elementary segments $\Delta t = \frac{t_{srch}}{n}$. The mathematical mean value of the number of detections per time interval Δt is equal to $\gamma \Delta t$. In accordance with the property of flow ordinariness, the probability of two or more detections falling into a small time interval may be neglected. Therefore, the probability of only one detection in time Δt may be considered approximately equal to $\gamma \Delta t$ (within the accuracy up to infinitesimal quantities of higher order $\Delta t \to 0$).

Therefore, we can assume that the probability of at least one detection during time Δt is approximately equal to $P = \frac{\gamma t_{srch}}{n}$, and the probability of the opposite event (no detections) in time Δt is approximately equal to $q = 1 - \frac{\gamma t_{srch}}{n}$.

Since, in accordance with the condition of absence of aftereffects, the number of detections in non-overlapping periods is independent, it is possible to detect *n* independent experiments and apply the theorem of experiments repetition on this basis [3]. In accordance with this theorem, probability P_{mn} that among *n* periods there will be exactly in *m* periods is equal to the corresponding member of binomial distribution (2)

$$P_{mn} = C_n^m p^m q^{n-m} = C_n^m \left(\frac{\gamma t_{srch}}{n}\right)^m \left(1 - \frac{\gamma t_{srch}}{n}\right)^{n-m}, \qquad (2)$$

where C_n^m is the number of combinations of *n* elements by *m*.

Since, due to the property of flow ordinariness, the probability of two detections in elementary interval *t* is negligible, then with $n \rightarrow \infty$, probability P_{mn} becomes approximately equal to the searched probability P_m of obtaining exactly the specified number of detections *m* during time of search t_{srch}, and

$$P_m = \lim_{n \to \infty} C_n^m \left(\frac{\gamma t_{srch}}{n}\right)^m \left(1 - \frac{\gamma t_{srch}}{n}\right)^{n-m} \qquad (3)$$

The expression under the limit sign in formula (3) can be transformed as follows (4):

$$C_n^m \left((\gamma t_{srch})/n\right)^m \left(1 - (\gamma t_{srch})/n\right)^{(n-m)} = \left(n(n-1)\ldots(n-m+1)(\gamma t_{srch})^m \left[\left(1 - (\gamma t_{srch})/n\right)\right]^n\right)/\left(m!\, n^m \left[\left(1 - (\gamma t_{srch})/n\right)\right]^m\right) == \left(n(n-1)\ldots(n-m+1)(\gamma t_{srch})^m\right)/\left(n^m m!\right) \times \left[\left(1 - (\gamma t_{srch})/n\right)^n\right. \qquad (4)$$

With $n \rightarrow \infty$, the first fraction, and the denominator of the last fraction tend to the unity, and the numerator of the last fraction - to $e^{-\gamma t_{srch}}$ (important limit). Thus, the required probability P_m of getting exactly the specified number of detections *m* during time of search t_{srch} is expressed by formula (5)

$$P_m = (\gamma t_{srch})^m \frac{e^{-\gamma t_{srch}}}{m!} \qquad (5)$$

Here $\gamma t_{srch} \rightarrow$ is the average number of detections during search time t_{srch}. In the search theory, this value is called the search detection potential, and is denoted as *U*(6).

$$P_m = (U)^m \frac{e^{-U}}{m!} \qquad (6)$$

In cases where intensity of flow of detections changes over time (7) (a non-stationary Poisson flow), this value is

$$U = U(t_{srch}) = \int_{t_0}^{t_0 + t_{srch}} \gamma(\tau) d\tau, \qquad (7)$$

where t_0 is the time of search start.

Since in many cases solving the search problem requires only one object detection, it is important to be able to calculate the probability of at least one (not less than one) detection during search time $P_{m\geq 1}$. This probability can be obtained from the apparent equation $P_{m\geq 1} = 1 - P_{m=0}$. Value $P_{m=0}$ (8) is found using formula (6) for *m = 0*:

$$P_{m=0} = \left(\frac{U^0}{0!}\right) e^{-U} = e^{-U} \qquad (8)$$

Therefore, $P_{m\geq 1} = 1 - e^{-U}$.

In the theory of search, the resulting probability of at least one object detection $P_{m\geq 1}$ is often simply called probability of detection, and is denoted P_{det} (9), which for a non-stationary Poisson flow is equal to

$$P_{det} = P_{det(t)} = 1 - e^{-U(t)} = 1 - exp\left[- \int_{t_0}^{t_0 + t} \gamma(\tau) d\tau\right] \qquad (9)$$

Since we are interested in the probability of detection over time elapsed from fire outbreak, formula (9) takes the form:

$$P_{det} = P_{\det(t)} = 1 - e^{-U(t)} = 1 - exp\left[- \int_{t_0}^{t} \gamma(\tau)d\tau\right], \qquad (10)$$

where t is the time elapsed from fire outbreak, and t_0 is the moment of the monitoring tool activation.

The method of assessing detection intensity of a function of time and distance

Let us consider in more detail the search intensity of a non-stationary Poisson flow for a certain forest fire monitoring tool. Search intensity depends on the complex of all physical conditions. For example, in case of visual search, it depends on the distance between the target and the observer, on the meteorological conditions, on size and brightness of the target, as compared to the surrounding background, the observer's abilities, observation height, etc. Another important factor is the fact of the forest fire parameters changing over time (fire propagates).

Therefore, we will consider search intensity as function (11) of several variables

$$\gamma = \gamma(t, r, \ldots), \qquad (11)$$

where r *is* the distance between the observer and the fire, t is the time since fire outbreak. We will consider the influence of the distance to the fire, and the time since fire outbreak. Search intensity is proportional to solid angle Ω which subtends the area of the forest fire from the observation point. The entire area of forest fire S may be divided into elementary rectangles with the area of *ab.*

Let us find the solid angle subtending such a rectangle. Figure 1 shows the layout of an observation tool and a forest fire.

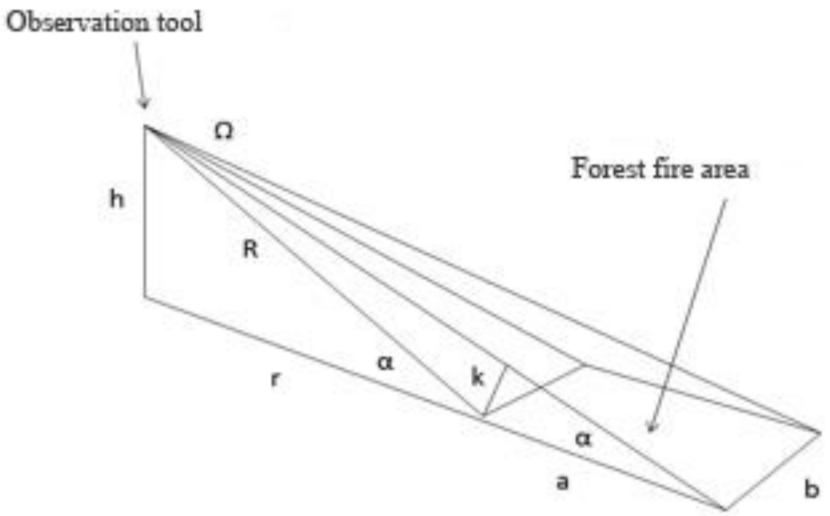

Fig. 1. Layout of an observation tool and a forest fire

From similarity of triangles, we get $\alpha = \frac{h}{R} = \frac{k}{a}$. From which $k = \frac{ha}{R}$. Let's denote $\Omega_1 = \frac{k}{R} = \frac{ha}{R^2}$ and $\Omega_2 = \frac{b}{R}$.

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Then the searched solid angle is equal to $\Omega = \Omega_1 \Omega_2 = \frac{\boldsymbol{h}a}{R^2} \times \frac{b}{R} = \frac{\boldsymbol{h}ab}{R^3}$. Since $\boldsymbol{h} \ll r$, then $r \approx R$. We get: $\Omega = \frac{\boldsymbol{h}ab}{r^3}$. Summing the solid angles for all rectangles into which the area of the forest fire was divided, we get that the solid angle subtending the entire area of the forest fire is equal to $\Omega_s = \frac{\boldsymbol{h}S}{r^3}$, where *S* is the area of the forest fire.

Let's assume that fire spreads around the circumference, the radius of which increases with constant speed v_r. Then the dependence of fire speed on time may be represented as $S = \pi(v_r t)^2$, and search intensity (12) is equal to

$$\gamma(t, r) = K\Omega_s = \frac{K\boldsymbol{h}S}{r^3} = \frac{K\boldsymbol{h}\pi(v_r t)^2}{r^3}, \qquad (12)$$

where *K* is the coefficient of proportionality.

Let's substitute the obtained search intensity into (10), and we will assume that *r* is the specified parameter, then we get

$$P_{det} = P_{\det(t)} = 1 - e^{-U(t)} = 1 - exp\left[-\int_{t_0}^{t} \frac{K\boldsymbol{h}\pi(v_r \tau)^2}{r^3} d\tau\right] \qquad (13)$$

Let's assume that the start of observations coincides with the fire outbreak, i.e. $t_0 = 0$.

$$P_{det} = P_{\det(t)} = 1 - e^{-U(t)} = 1 - exp\left[-\int_{0}^{t} \frac{K\boldsymbol{h}\pi(v_r \tau)^2}{r^3} d\tau\right] = 1 - exp\left[-\left(\frac{K\boldsymbol{h}\pi {v_r}^2 t^3}{3r^3}\right)\right] \qquad (14)$$

Let us find the density of this distribution by differentiating the function from expression (14) by *t.*

$$f(t) = exp\left[-\left(\frac{K\boldsymbol{h}\pi {v_r}^2 t^3}{3r^3}\right)\right]\frac{K\boldsymbol{h}\pi {v_r}^2 t^2}{r^3} \qquad (15)$$

To find *K* from equation (15), it is necessary to perform the following experiment.

The monitoring tool should be set at certain height *h, a* controlled forest fire with some constant propagation rate v_r should be started at distance *r* from the monitoring tool. Using the monitoring tools under study, start monitoring the forest area from the time of fire outbreak. It is necessary to note the time of fire detection with this monitoring tool.

This experiment should be performed several times. After that, we get several detection times. Let us divide the entire time scale into *m* intervals with some increment. Let's denote the center of each interval as t_i. To each interval we assign number n_i that is equal to the number of detection times obtained during the experiments, and falling into the $i - \boldsymbol{th}$ interval. Let's normalize the number of detection times from each interval, by dividing them by the total number of detection times obtained from the experiment. Thus, for each of *m* intervals, we will get number k_i from relation (16)

$$k_i = \frac{n_i}{\sum_{i=1}^{m} n_i} \qquad (16)$$

Therefore, after the experiment, we will have the data shown in Table 1.

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Table 1. Data obtained from the experiment

X	Y
t_i	k_i

We will also obtain a family of following functions with unknown parameter *K.*

$$y(x) = exp\left[-\left(\frac{Kh\pi v_r^2 x^3}{3r^3}\right)\right]\frac{Kh\pi v_r^2 x^2}{r^3} \quad (17)$$

For the data in Table 1 and family of functions (17), let us perform the regression analysis, and get the value of parameter *K*. Thus, we will find all the parameters for finding the probability of forest fires detection during time *t*, using formula (4) for each detection tool.

These considerations have been shown for the case when the distance between the detection tool and the fire does not change during the observation. If the distance changes during the observation (the monitoring tool is moving relative to the fire, for example, in case of aerial surveillance and ground patrolling) according to some rule *r(t)*, it is necessary to substitute this rule of distance changing into formula (10), and we will get

$$P_{det} = P_{\det(t)} = 1 - e^{-U(t)} = 1 - exp\left[-\int_{t_0}^{t}\frac{Kh\pi(v_r\tau)^2}{r(\tau)^3}d\tau\right] \quad (18)$$

Coefficient K from relation (18) for this detection tool can be obtained after static tests (in case of a fixed distance between the observation tools and the fire), as in the experiment above. As the family of approximating functions, we will use the function of probabilities distribution given by equation (14), rather than the density of probabilities distribution defined by relation (17). This changes the rules of calculating experimental values of k_i(19). Namely,

$$k_i = \frac{\sum_{i\leq 1} n_s}{\sum_{i=1}^{m} n_i} \quad (19)$$

Further, similar to the previous experiment, we populate values *r, h, t, k* into Table 1, build a nonlinear regression model, thus determining the value of parameter *K*.

The arguments above are true for monitoring tools that use for monitoring the principles of analyzing waves emitted by the object of observation (optical monitoring, infrared monitoring). For detecting a fire with the use of Autonomous Fire Detectors (AFD) that use other principles of fire detection, we will use the following model.

Let an AFD be placed at distance *r* from the fire, then the fire will reach the location of AFD in time $t_{frch} = \frac{r}{v_{av}}$, where v_{av} is the average velocity of fire propagation.

In this case, the probability of fire detection by the AFD in time *t* is equal to

$$P_{\det(t)} = \begin{cases} 0, if \frac{r}{v_{av}}, > t, \\ 1, if \frac{r}{v_{av}}, < t. \end{cases} \quad (20)$$

The probability of fire non-detection by the AFD in time *t* will, accordingly, be equal to

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$$Q_{\det(t)} = \begin{cases} 0, if \dfrac{r}{v_{av}}, < t, \\ 1, if \dfrac{r}{v_{av}}, > t. \end{cases} \qquad (21)$$

The method of calculating the probability of forest fire detection with several monitoring tools via search intensity

Above, we have considered the probability of detecting a forest fire with a single monitoring tool, which by the property of fire detection was characterized by search intensity $\gamma(t, r)$. However, it is possible to build such monitoring systems where monitoring is performed by two or more monitoring tools. In other words, a certain monitoring system is created, which, similar to a single monitoring tool, can detect forest fires. In this case, it is possible to characterize such a system from the probabilistic point of view by the property of detection.

Let us consider the simplest case, where the system consists of two observation tools that are generally different and located at distance *d* relative to each other. For simplicity of consideration, let us assume that the distance between the monitoring tools does not change over time.

Let the first monitoring tool be characterized by search intensity $\gamma_1(t, r)$, and the second - by $\gamma_2(t, r)$. Let's assume that the fire is at arbitrary point *A* (Fig. 2). Values γ_1 and γ_2 in this case will depend on respective distances R_1 and R_2. Let's assume that $\gamma_1 = \gamma_1(t, R_1)$ and $\gamma_2 = \gamma_2(t, R_2)$.

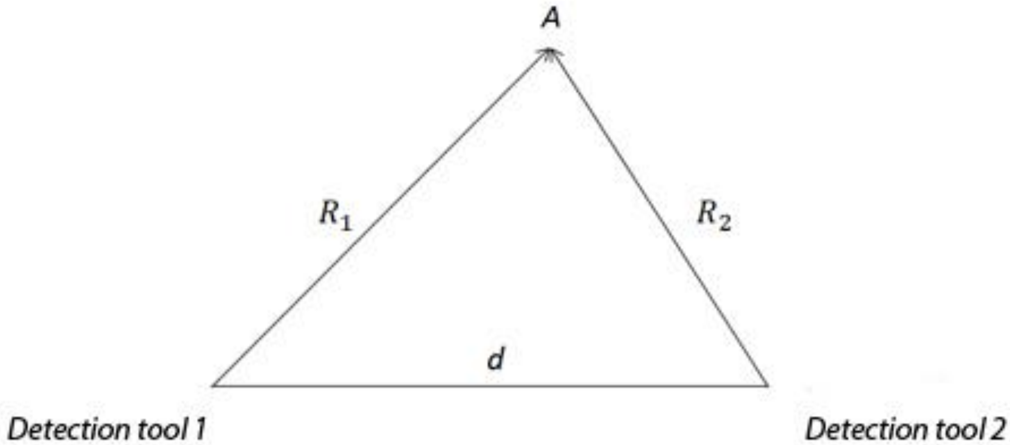

Fig. 2. A monitoring system consisting of two detection tools

Let's assume that both tools start monitoring since the start of the fire. Then the probability of fire detection by the first and the second monitoring tools, according to formula (2) with observing it during time *t*, will be determined from equations (22) and (23):

$$P_{det1}(t) = 1 - exp\left[-\int_0^t \gamma_1(\tau, R_1)d\tau\right], \qquad (22)$$

$$P_{det2}(t) = 1 - exp\left[-\int_0^t \gamma_2(\tau, R_2)d\tau\right] \qquad (23)$$

For the fire located at point *A* to be undetected, it is necessary that it is not detected by either monitoring tool. Assuming independent operation of the detection tools, we get the probability of non-detection from equation (24)

$$Q_{1,2}(t) = e^{-\int_0^t \gamma_1(\tau,R_1)d\tau} e^{-\int_0^t \gamma_2(\tau,R_2)d\tau} = e^{-\int_0^t \lbrack(\gamma\rbrack_1(\tau,R_1)+\gamma_2(\tau,R_2))d\tau}, \qquad (24)$$

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and probability of detection, respectively, from equation (24)

$$P_{1,2}(t) = 1 - Q_{1,2}(t) = 1 - e^{-\int_0^t (\gamma_1(\tau,R_1)+\gamma_2(\tau,R_2))d\tau} \qquad (25)$$

Formula (24) characterizes the probability of detecting a fire located at point *A* not by a single monitoring tool, but by the system (in this case, two detection tools).

If the detection system is complemented with AFDs, equation (25) will look as follows (26):

$$P_{1,2}(t) = 1 - Q_{1,2}(t)Q_{\det(t)}, \qquad (26)$$

where $Q_{\det(t)}$ is the probability of fire detection by AFDs in time *t* (21).

In may be concluded that if there is a monitoring system consisting of *k* AFDs and *m* other monitoring tools, the probability of detecting a fire at point *A* in time *t* will be defined as (27):

$$P(t) = 1 - e^{-\int_0^t \sum_{i=1}^m \gamma_i(\tau,R_i)d\tau} Q_{1\det}(t) \dots Q_{k\det}(t) \qquad (27)$$

Let us find the probability of fire detection by the monitoring system in time *t*, depending on the location of the monitoring tools in the system. Let there be a monitoring system of *k* AFDs and *m* other monitoring tools located arbitrarily on the plane. Let's choose a rectangular system of coordinates. The reference point may be at any point on the plane. The location of each monitoring tool on the plane will be characterized by the X and Y coordinates of its position in the selected system of coordinates, and the structure of the entire monitoring system may be defined by sequence $\{X_1Y_1, X_2Y_2, \dots, X_iY_i, \dots, X_nY_n\}$, , where X_iY_i are the coordinates of the *i*-th monitoring tool. Search intensity of each monitoring tool (not AFD) may be defined by function $\gamma_i(t, R_i)$. Let us take an arbitrary point on the plane with coordinates *xy*. The distance between point *xy* and the *i*-th monitoring tool will be determined as (28t):

$$R_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2} \qquad (28)$$

Then at point *xy*, the search intensity for the *i*-th monitoring tool (not AFD) will have the value of $\gamma_i = \gamma_i(t, R_i)$.

Thus, the probability of detecting a fire at arbitrary point *xy* in time *t* by a monitoring system consisting of *k* AFDs and *m* other monitoring tools, with search intensity $\gamma_i(t, r)$ located at points with coordinates X_iY_i , respectively, will be defined by formula (29)

$$P(x,y,t) = 1 - e^{-\int_0^t \sum_{i=1}^m \gamma_i\left(\tau, \sqrt{(x-x_i)^2 + (y-y_i)^2}\right)d\tau} \times Q_{1\det}\left(t, \sqrt{(x - X_{1\det})^2 + (y - Y_{1\det})^2}\right) \dots Q_{k\det}\left(t, \sqrt{(x - X_{k\det})^2 + (y - Y_{k\det})^2}\right) \qquad (29)$$

Methods of calculating integral indicators of effectiveness of territorial natural fires monitoring systems functioning from the standpoint of early detection

Complexity of presenting the value for a number of damage components, and the lack of adequate accounting of the negative consequences of forest fires complicate the possibility of calculating the absolute value of damage from fires for individual territories. Acceptability of using comparative effectiveness indicators in the optimization calculations allows getting from the absolute damage values to the relative ones. Using relative indicators excludes the possibility of economic substantiation of the optimal level of costs for protection, as described earlier, but allows solving problems of optimum allocation of resources for protection and its optimal strategies [6-10].

Implementation of tasks of ensuring timely detection and extinguishing (elimination) of fires in the forest fund and in forests outside the forest fund requires that territorial bodies of the Federal Forestry Authority to create and properly organize work of specialized on-ground and aerial forest fire services equipped with modern tools for detecting and suppressing fires [4, 5]. With that, operation of these forced and tools should be organized so that every fire in the forest is detected at early stages of development, or at the time of outbreak, and the message about the fire is immediately passed to the appropriate service that would organize fire extinguishing so that the required forces and tools for fire extinguishing arrive in due time to the location of the fire and ensure its extinction in the shortest possible time.

To assess the effectiveness of the forest fire protection system, it is proposed to consider the average expected indicator of effectiveness of monitoring the forest fire danger (the criterion of timely forest fires detection) for a specified territory [15, 16].

Let some area *S* be considered. In this area, a finite set of possible actions is considered for monitoring the danger of forest fires, which are characterized by the type, volume and location on this area in the quantity of m. Assume that vector $= (z_1, z_2, \dots, z_m)$ is the vector of incendency of choosing the monitoring activities, namely $z_i = 1$, if the *i*-th activity is selected for implementation, and $z_i = 0$ otherwise.

Let's introduce several notations:

(x,y) - the coordinates of fire break-out point;
$\vartheta(x,y)$- time of fire-fighting forces arrival;
I is the category of fire hazard;
$T_{cr.}((x,y),I)$ is the detective time fire fighting forces arriving at point *(x,y)* depending on the category of fire hazard;
t_{cr} is the critical (maximum) time of fire detection calculated based on equation (30):

$$t_{cr}(x,y) = \max\big(T_{cr}((x,y),I) - \theta(x,y); 0\big); \quad (30)$$

$P_c((x,y),t)$ is the probability of fire detection at point *(x,y)* in time *t* by the *k*-th monitoring tool;
A(x,y) is the event of fire detection at point *(x,y);*
T(A(x,y)) is a random value - time of fire detection at point *(x,y); and*
F(x,y) is the conditional probability of fire detection at point *(x,y)* in the maximum allowable time t_{cr} by the entire set of monitoring tools, the value of which is calculated by formula (31):

$$F(x,y) = 1 - \prod_{k=1}^{N} \left[\left(1 - P_k\left((x,y), t_{cr}(x,y)\right)\right) \right], \quad (31)$$

The procedure for calculating t_{cr} - the critical (maximum) time of fire detection is shown in Fig. 3

$$\begin{tikzcd} (x,y) \arrow[r] \arrow[d] & \theta(x,y) \arrow[d] \\ T_{кр.}((x,y),I) \arrow[r] & t_{кр}(x,y) \end{tikzcd}$$

Fig. 3. The scheme for calculating t_{cr}.

The maximum value of $T_{cr.}((x,y),I)$ for forests classified as class I of natural fire danger should be not later than one hour from the moment of fire outbreak; for the forests classified as class I of natural fire danger - not later than 2 hours from the moment of fire outbreak; for forests classified as class 3 and 4 – not later than 3 hours from the moment of fire outbreak.

Then it is advisable to consider value

$$Q_s = \frac{\iint_S F(\mathbf{x}, \mathbf{y})\, ds}{S_{frst}}, \qquad (32)$$

as the forest fire danger monitoring system effectiveness indicator, where Q_s is the indicator of the monitoring system effectiveness in the area,

S is the coverage area of the forest, and
S_{frst} is the area of forest coverage S.

It is possible to consider the cost characteristics of individual forest areas in the form of modified indicator

$$QV_s = \frac{\iint_S v(x, y) F(\mathbf{x}, \mathbf{y})\, \mathbf{ds}}{S_{frst} \iint_S v(x, y)\, ds}, \qquad (33)$$

where QV_s is the indicator of effectiveness of the fire danger monitoring system in the territory with regard to the value of the forest, and v(x,y) is the spot characteristic of the forest value.

Indicators Q_s(32) and QV_s(33) are absolute indicators that depend on the established system of forest protection described by vector z and by the amount of financial resources V_B , i.e. $Q_s(z, V_B)$ and $QV_s(z, V_B)$. From the point of view of integration, it is useful to consider the relative indicators that characterize the quality ratio of the existing system to the most effective one under the same financial restrictions.

Let us consider the following indicators:

$$RQ(z) = \frac{Q(z^{*}, V_B)}{Q(z^{\square}, V_B)} \qquad (34)$$

and

$$RQV(z) = \frac{QV(z^{*}, V_B)}{QV(z^{\square}, V_B)}, \qquad (35)$$

where, as above, z^* is the most effective system of forests protection established under financial restrictions V_B. The higher indicators RQ(34) and RQV(35) are, the more efficient is the creation of a forest fire danger monitoring system in area S within budget V_B.

The method of assessing effectiveness of forest fire danger monitoring system functioning based on grid approximation

Let us consider some area G that is completely or partially covered by forests of various types. Assume we know characteristics of forest plots in this territory [11]. These are the species composition and the forest condition [12]. Forest fire danger monitoring tools [17], their characteristics and location are known. It is necessary to assess the effectiveness of this forest fires detection system operation.

The following sequence of solving this problem is proposed. For all plots, forest fire hazard class is determined. Each forest area will belong to one of five classes of natural fire danger. Next, we combine plots belonging to the same class. In the end, we get this area divided into sections with certain classes of natural fire danger. Next, for simplicity of formulas, we will consider a monitoring system consisting of monitoring tools not belonging to AFDs.

As noted above, for each class of natural fire danger, the recommended time of a fire brigade arrival to fight against the fire is defined as follows: for the areas belonging to natural fire danger class I - not later than one hour after fire outbreak; for the areas belonging to class II - no later than two hours; for the areas belonging to classes III-IV - three hours after fire outbreak. Thus, for each forest site in this territory, the recommended arrival time for the fire brigade is known.

In this area *G* of the forest, *m* monitoring tools are located arbitrarily on the plane, with their monitoring zones in area *G*. Let's choose a rectangular system of coordinates. The reference point may be at any point on the plane.

Let us divide area *G* into several rectangular plots by lines parallel to the coordinate axes. To do so, let us note points x_1, x_2, ..., x_ξ,..., x_n on the *X*-axis, and points y_1, y_2, ..., y_η,..., y_k - on the *Y*-axis. In general case, the distance between these points may be different.

Due to the fact that area *G* has been divided into rectangles, we get a set of intersection points between the lines that are parallel to the coordinate axes; the number of these points will be determined by product *nk*, and their coordinates may be put in the form of the following sequences:

$$\begin{gathered}
(x_1, y_1),\ (x_1, y_2),\ \ldots,\ (x_1, y_\eta),\ldots,\ (x_1, y_k);\\
(x_2, y_1),\ (x_2, y_2),\ \ldots,\ (x_2, y_\eta),\ldots,\ (x_2, y_k);\\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
(x_\xi, y_1),\ (x_\xi, y_2),\ \ldots,\ (x_\xi, y_\eta),\ldots,\ (x_\xi, y_k);\\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
(x_n, y_1),\ (x_n, y_2),\ \ldots,\ (x_n, y_\eta),\ldots,\ (x_n, y_k).
\end{gathered}$$

Thus, generally the coordinates of any grid point in area *G* may be written as (x_ξ, y_η), , where ξ = 1, 2, ..., *n*; η = 1, 2, ..., *k*.

Each point (x_ξ, y_η) of the grid falls into a certain plot of the forest, for which we know the recommended fire brigade arrival time, from the moment of fire outbreak. We know the location of fire brigade in this area. That is, we know its coordinates $X_{\mathbf{brgd}}$ and $Y_{\mathbf{brgd}}$. The time of fire brigade arrival to the location of fire is the amount of time during which the fire is detected by the monitoring system, and the time during which the fire brigade arrives at the destination point.

Therefore, the critical time of detection may be calculated as: $t_{\mathbf{cr}} = t_{\mathbf{rec}} - t_{\mathbf{arr}}$, where $t_{\mathbf{cr}}$ is the critical time of fire detection by the monitoring system, $t_{\mathbf{rec}}$ is the recommended fire brigade arrival time to the location of fire, and $t_{\mathbf{arr}}$ is the time of fire brigade arrival at the location of the fire.

For each point on the grid, $x_\xi y_\eta$ can be calculated. In the simplest case, it can be calculated as

$$t_{\mathbf{arr}} = k\frac{\sqrt{(x_\xi - X_{\mathbf{brgd}})^2 + (y_\xi - Y_{\mathbf{brgd}})^2}}{v_{\mathbf{brgd}}}, \qquad (36)$$

where $v_{\mathbf{brgd}}$ is the speed of the fire brigade travel, and *k* is the coefficient that takes into account the non-straight and uneven nature of the fire brigade's path to the location of fire. Thus, for each point on the grid (x_ξ, y_η), we know critical time $t_{\mathbf{cr}\,\xi\eta}$, in which the forest fire at this point is to be detected by the monitoring system.

The location of each monitoring tool on the plane will be characterized by the X and Y coordinates of its position in the selected system of coordinates, and the structure of the entire monitoring system may be defined by sequence $\{(X_1, Y_1), (X_2, Y_2), \ldots, (X_i, Y_i), \ldots, (X_m, Y_m)\}$, where (X_i, Y_i) are the coordinates of the *i*-th monitoring tool.

The distance from the *i*-th monitoring to the monitored point (x_ξ, y_η) is equal to

$$R_i = \sqrt{(x_\xi - X_i)^2 + (y_\eta - Y_i)^2} \qquad (37)$$

For each monitoring tool, we know search intensity $\gamma_i(t, \quad R_i)$. It is determined by the method described above. Then, according to formula (29), the probability of fire detection by the monitoring system with this configuration of monitoring tools and their location at the point $[(x]_\xi, y_\eta)$ in time $t_{cr\ \xi\eta}$ will be equal to

$$P = 1 - e^{-\int_0^{t_{cr\ \xi\eta}} \sum_{i=1}^{m} \gamma_i\left(\tau, \sqrt{(x_\xi - X_i)^2 + (y_\eta - Y_i)^2}\right) d\tau} \qquad (38)$$

Let's sum this value for all grid points that cover the specified area *G*, using the squares of the elementary sites as weights. We will get the value that would characterize the effectiveness of forest fire detection by this detection system in area *G* within the critical time of detection.

$$F = \sum_{\eta=1}^{k} \sum_{\xi=1}^{n} \left(1 - e^{-\int_0^{t_{cr\ \xi\eta}} \sum_{i=1}^{m} \gamma_i\left(\tau, \sqrt{(x_\xi - X_i)^2 + (y_\eta - Y_i)^2}\right) d\tau}\right) S[(x]_\xi, y_\eta), \qquad (39)$$

where $[S(x]_\xi, y_\eta)$ is the area of the elementary plot.

Value F, which is the average probability of timely forest fire detection in certain area, can be used for assessing effectiveness of functioning of a particular fire detection system in the area.

CONCLUSIONS

This article considers the process of detecting forest fires as a non-stationary variable intensity Poisson stream. A formula has been developed for determining the probability of fire detection within specified time from the beginning of fire outbreak.

The method of determining the characteristics of instantaneous probability of fire detection has been developed in course of full-scale tests for various monitoring tools.

Equations for calculating the probability of forest fire detection by several monitoring tools are presented.

Absolute and relative indicators for assessing efficiency of forest fire monitoring systems functioning from the point of view of timeliness of detection have been developed and presented. Equations for calculation are presented.

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