METHODOLOGY OF ASSESSING SOCIAL DAMAGE FROM LONG-TERM SMOKE DURING FIRES IN MOUNTAIN FOREST BELTS OF RUSSIA

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Abstract

The article describes a methodology for assessing social damage during fires in mountain forest belts of the Russian Federation, associated with an increase in the overall mortality of the population as a result of long-term and intense smoke in urbanized areas. The relevance of the topic and the demand for the results are associated with the growing number of forest fires, including in mountainous areas, with changing consequences, both for the ecology of regions and human economic activity, and for the life and health of the population, changing consistent long-term smoke pollution of urbanized areas. Recently, many countries have been paying more and more attention to the pollution of the atmosphere of populated areas, namely, air quality is a determining factor for the health and life expectancy of the population. The methodology presented in the article allows us to estimate the concentration of fine particles in space at a given distance from a forest fire and to estimate the possible social damage associated with the formation of general mortality as a result of smoke pollution. An example of testing this methodology is given using the example of long-term smoke in Moscow in 2010.

Keywords: forest fire, social damage, smoke, fine particles.

I Introduction

In the Russian Federation, more than one third of the territory is mountainous - these are the Urals, the North Caucasus, the mountains of Southern Siberia, the mountains of Eastern Siberia, and the Far East. Mountain forests of deciduous and coniferous trees in our country and neighboring countries occupy a huge area – about 45% of the total area of the country's forest fund.

They are characterized by vertical zoning with a slope steepness of ridge slopes with increasing altitude.

Recently, more and more attention has been paid to air pollution in populated areas in our country, since air quality is a key factor influencing the health and life expectancy of the population. Numerous studies have shown that the main contribution to the deterioration of health and the increase in overall mortality of the population is made by finely dispersed substances with an aerodynamic diameter of 10 micrometers or less (hereinafter – PM10) and 2.5 micrometers or less (hereinafter – PM2.5) in the atmosphere of urbanized areas. One of the main sources of fine particles PM10 and PM2.5 in the atmosphere are wildfires. Studies show [1] that about 44% of all fine particle emissions per year come from forest fires. Fires release significant amounts of smoke and ash containing significant concentrations of these fine particles, which spread over significant distances in the atmosphere. The US National Institute for Health Effects Research analyzed morbidity and mortality statistics and established a quantitative relationship between air pollution by suspended particles with an aerodynamic diameter of less than 10 μm – PM10 and overall mortality. With an increase in the average daily concentration of dispersed particles by every 10 $\mu g/m^3$, daily mortality from all causes, except accidents, increased by an average of 0.5% the next day. Similar studies were conducted in 30 regions of Europe. The results of studies in Europe are in good agreement with the results obtained earlier in the USA [2]. In the works of the Chief State Sanitary Doctor of Russia (1996-2013) Onishchenko G.G [3] it was also proposed to calculate the increase in the average daily mortality from all causes, except accidental deaths, by 0.5% with an increase in the average daily concentration of dispersed particles by every 10 μg/m3. Epidemiological studies conducted in Western Europe have shown that the statistical relationship between mortality and the levels of PM2.5 concentration in the air is much stronger than with the levels of PM10 particle concentration (average annual concentration of suspended matter) [4]. Thus, with an increase in the average daily concentration of PM2.5 dispersed particles by every 5 μg/m3, the average daily mortality from all causes, except accidental deaths, increases by 0.7%.

II Main part

Substances emitted as a result of a forest fire in the form of gases and aerosols form a cloud that spreads in the direction of the wind. When gas contamination is detected in advance using the forecasting method, the most probable and closest to real meteorological conditions at different times of the year (day) are used as initial data. The possible type of forest fire is determined. It is recommended to calculate the gas contamination of the territory based on the worst meteorological conditions in terms of the formation of gas contamination zones and the impact of combustion products: wind speed; atmospheric stability; time of day; seasonality; the settlement (economic facility) is located on the axis of the trace of the spread of combustion products. Based on the values of the increase in mortality with an increase in the concentration of fine particles in the atmosphere of urbanized areas obtained in the works [2, 4], it is assumed that:

- with an increase in the average daily concentration of dispersed particles PM10 for every 10 μg/m3, the average daily total mortality from all causes, except accidental deaths, increases by 0.5%.
- with an increase in the average daily concentration of dispersed particles PM2.5 for every 5 μg/m3, the average daily total mortality from all causes, except accidental deaths, increases by 0.7%.

The initial data for the calculations are:

1. the area of the forest fire (hereinafter referred to as FF) upon detection,
2. wind speed as measured at the weather station for a height of 10 m,
3. the stock of forest combustible materials (hereinafter referred to as FCM) (tables 1-2),
4. the height of the forest tiers (tables 1-2),
5. the moisture content of FCM,
6. the population of the urbanized area under consideration.

Assumptions made:

1. The ground FF spreads with the direction of the wind, across the direction of the wind and against the wind.
2. The crown FF spreads only with the direction of the wind.
3. A crown fire exists only in the presence of a ground fire.
4. The contour of the FF is an ellipse. The major axis is directed downwind.
5. Combustion products are released only from the combustion zone along the perimeter of the fire. The width of the combustion zone is different in different zones of the fire perimeter.
6. The flame speed in different zones of the fire perimeter is different.
7. The burning time of the fire perimeter sections is the same for all sections.

Wind speed in a forest at a standard height of 10 m [4]:

— , (m/s) (1)

Where:
h_1 – height of the first tier of forest massif (tables 1-2);
h_3 – height of the third tier of forest massif (tables 1-2);
N – empirical multiplier (table 3);
– wind speed as measured at a weather station for a height of 10 m.

Table 1: *Forest fuel model [5]*

The main conductor of combustion is dried grass	
Model 1. (low grasses)	Areas covered with dried or drying grasses (mainly cereals) about 0.3 m high; the canopy density of trees and shrubs does not exceed 0.3 (meadows, savannas, grassy tundra)
Model 2. (forest grasses and undergrowth)	Areas with a layer of forest fuel material in the form of a mixture of dried grasses and fallen trees and shrubs. These are open shrub landscapes, pine forests, stands of coppice oak; canopy density is 0.3-0.6
Model 3. (tall grasses)	Areas covered with dried or drying grasses about 1 m high. These are areas with wild and cultivated cereals, as well as tall grasses in swamps.
The main conductor of combustion is the canopy of bushes or their litter	
Model 4 (bushes)	Dense thickets of flammable bushes about 2 m high and undergrowth up to 6 m, as well as plantations with a dense flammable layer of undergrowth and undergrowth. There is a significant reserve of ground forest fuel materials (litter, dried grass).
Model 5 (low shrubs)	Thickets of non-flammable (young) bushes or plantations with a dense layer of non-flammable undergrowth and young trees, deciduous young trees. The combustion conductor is litter
Model 6 (drying shrubs and cluttered hardwoods)	Areas similar to those in model 4, but the bushes are not as tall and do not contain much fuel, so they can only burn actively when the wind speed is over 4 m/s
Model 7 (southern weeds)	Thickets of flammable shrubs from 0.5 to 2 m in height, as well as plantations with a low flammable layer of undergrowth and young growth
The main conductor of combustion is forest litter and deadwood	
Model 8 (closed forest litter)	Closed stands of short-needled trees (spruce, fir, white pine, larch) and closed stands of aspen and birch, as well as hardwoods (in summer). The main fuel is compacted litter.
Model 9 (hardwood litter)	Closed stands of long-needle trees (Ponderosa pine, red pine, southern pine, etc.), as well as oak and maple (in winter). The main combustibles are loose litter.
Model 10 (forest litter and undergrowth)	Plantations littered due to damage by insects, wind or due to overmaturity. Old clearings in coniferous plantations.
The main conductor of combustion is logging residues	
Model 11 (light logging residues)	Non-continuous fellings, thinning areas with undeleted logging residues, usually in coniferous and hardwood stands
Model 12	Clear and conditionally clear cuts with a significant stock of logging

(medium logging residues)	residues (up to 16 t/ha with a layer height of 0.7 m). Fires are strong, "spotted"
Model 13 (heavy logging residues)	Clear-cut areas in mature and overmature coniferous stands, heavily littered, mainly with large logging residues (up to 90 t/ha). Fires are strong, "spotted"

Table 2: *Characteristics of forest layers [5, 6]*

Model No.	*h* (height of the tier of the FCM layer)	*m* (mass of the FCM stock) kg/m^2
1st tier, h_1 – mosses and lichens		
-	0,15	3
2nd tier, h_2 – herbal group		
1	0,3	0,18
2	0,3	0,98
3	0,8	0,74
3rd tier, h_3 – shrub group and undergrowth		
4	6,0	3,92
5	0,6	0,84
6	1,9	1,48
7	0,8	1,39
4th tier, h_4 – crown		
8	20-30	6,3
9	20-30	7,06
10	20-30	8,08
Group of clearings		
11	0,3	2,80
12	0,7	8,49
13	0,9	14,3

Table 3: *N value depending on forest canopy density [6]*

Forest canopy closure	The value of the empirical factor *N*
0	0,77
0,2	0,62
0,4	0,47
0,6	0,32
0,8	0,165
1	0,09

Wind speed in the forest in the tree crowns (in the fourth tier of the forest) [6]:

$$, \text{(m/s)} \tag{2}$$

where *N* is an empirical factor, equal in this case to 0.77;
The burning time at the time of detection of the forest fire:

$$\sqrt{\frac{}{\pi\cdot(\omega \qquad _B)\cdot\omega}} \text{ (s)} \tag{3}$$

where:
ω_A – the speed of propagation of the lower FF downwind, m/s, (formulas 4-5);
ω_B – the speed of propagation of the lower FF against the wind, m/s (formulas 4-5);

ω_C – the speed of propagation of the lower FF perpendicular to the wind, m/s (formulas 4-5);

Calculation of the speed of propagation of the lower and upper FF ω_n (ω_A, ω_B, ω_C), which takes into account the steepness of the slope, is calculated using the formula of E.V. Konev [7]:

$$\frac{{}_1(U\ \ \alpha)\cdot(m_S/m_0)^n}{\left[1\ \ \ \frac{(\rho\ \ \ {}_0)}{}\right]\cdot[1\ \ \ \cdot(\ \ \ \ {}_0)+D\cdot(T\ \ \ {}_0)]},\ (m/s) \qquad (4)$$

$$\begin{array}{lllllll} & & \left(\alpha\ \ -\right) & (0), & \left(\alpha\ \ -\right) & (\pi) & \\ & [B\ (0) & (U\ \ \ \ )] & & (U\ \ \ \ ) & & \\ (\nu\ \ \alpha) & & & & \overline{} & & (5) \\ & & (\pi) & & (U\ \ \ \ ) & & \\ & \lfloor & (U\ \ \ \alpha) & & - & & \end{array}$$

$$(\beta)\ \ \begin{cases}(1\ \ \ \ 8^\circ)\ \ [1\ \ \ \ A\,(\beta\ \ \ 8^\circ)] \\ \ \ \ \ \ (1\ \ \ \ \beta) \\ \end{cases} \qquad (6)$$

where:

ω_n – the speed of spread of the ground fire front on the horizontal underlying surface;

m_s – the stock of forest fuel materials on the underlying surface;

m_0 – the stock of forest fuel materials on the underlying surface corresponding to the speed of spread $\omega=\omega_0$;

G_f = 0.3;

ρ_0 – the density of the layer on the horizontal surface at the speed of spread $\omega=\omega_0$;

n = (0.2-0.35) – empirical coefficient;

ν' – wind speed pulsation (ν'~1 m/s);

β – angle of inclination to the horizon of the terrain;

α – angle between the direction of the speed of spread of the fire front $\vec{\omega}$ and the wind speed;

$C, D, B1, B2, B3, B4, a, b, \omega_{n0}$ – empirical constants [6];

T_0, W_0 – standard initial temperature of the horizontal layer FCM and moisture content, respectively.

A ground fire can transform into a crown fire or a summit crown fire if the following condition is met [6]:

$$\sqrt{m\ \ \ \ \ \ \ \ } \qquad (7)$$

where:

h_l – height of the lower boundary of the forest canopy;

$H_{h.f.l.}$ – height of the flame of the lower FF (formula 19);

k_e – empirical coefficient equal to 8 for rags, grass and litter.

The area of the front of the lower FF during further spread of the fire at time t is calculated by the formula:

$$(m^2) \qquad (8)$$

where:

L_l – the perimeter of the lower FF contour (ellipse) at time t, m (formula 10);

Δ^l – the width of the combustion front of the lower FF, m (formula 14).

The area of a widespread crown forest fire is determined by the formula [8]:

$$- \ (\omega_A^c + \omega_\text{B}) \cdot \omega_\text{C} \cdot t^2 \ (\text{m}^2) \tag{9}$$

Where $\omega^c{}_A$ is the speed of spread of a crown forest fire by wind.

The perimeter of the lower FF contour at time t:

$$(t \qquad t)\big[0\ 75(\omega \qquad\qquad\qquad) \qquad 71\sqrt{(\omega \qquad\qquad)\omega_C}\big] \ (\text{m}) \tag{10}$$

The width of the combustion front of the lower FF in the direction of the wind is calculated using the formula of professor Albini [9]:

$$\left(\frac{4 \cdot (U_l)^2}{}\right) \quad (\text{m}) \tag{11}$$

where:

h_* – height of the forest layer involved in the FF, m (tables 1-2);

g – acceleration of gravity.

Width of the combustion front of the lower FF across the wind direction:

$$\left(\frac{C}{}\right) \qquad (\text{m}) \tag{12}$$

Width of the combustion front of the lower FF against the wind direction:

$$\left(\frac{B}{}\right) \cdot \Delta_a^l \ (\text{m}) \tag{13}$$

Average width of the combustion front of the lower FF:

$$\frac{}{} \ (\text{m}) \tag{14}$$

Mass burnout rate at
low FF:

$$\frac{K \cdot (\sum_l^I \qquad {}_i) \cdot \omega}{} \ (\text{kg/m}^2\text{·s}) \tag{15}$$

crown FF:

$$\frac{}{} \ (\text{kg/m}^2\text{·s}) \tag{16}$$

where:

n – number of forest layers involved in the combustion process;

K – coefficient of completeness of forest fuel combustion (formula 18);

m_{si} – forest fuel reserve in the l-th forest layer, kg/m² (for crown fire m_s – for the 4th layer, for ground fires m_s – for forest layers involved in the fire) (tables 1-2).

In case of a widespread crown fire, the mass burning rate:

$$(\text{kg/m}^2\text{·s}) \tag{17}$$

Combustion efficiency coefficient FCM:

$$\frac{}{} \tag{18}$$

where:

W – moisture content of the fuel;

W_* – critical moisture content of the fuel, upon reaching which the fuel does not burn. For crown FF W_*=0.9.

The height of the torch of the low FF is calculated using the formula [5]:

$$k\ \ \cdot\sqrt{\sum_{l=1}^{L} m_{sl}\cdot\omega}\ \text{(m)} \tag{19}$$

Where ω is the average speed of propagation of the lower FF:

$$\frac{}{}\ \text{(m/s)} \tag{20}$$

The height of a crown FF is calculated using the formula:

$$k\ \ \cdot\sqrt{\sum_{l=1}^{L} m_{sl}\cdot\omega^{c}}\ \text{(m)} \tag{21}$$

Height of convective column during FF [10]:

$$\cdot\sqrt{\frac{}{v\cdot|1\ \ \gamma|}}\qquad\text{(m)} \tag{22}$$

where:

T_f – flame temperature, K (table 4);

γ – air temperature gradient, K/m [11];

S_* – area of the combustion front of a ground fire or crown fire (S_B) m^2;

V_m – mass burnout rate of a ground fire ($V_{m.l.}$) or crown fire ($V_{m.c.}$).

Table 4: *The value of flame temperature depending on the type of forest fire*

Type of forest fire		Flame temperature T_f (K)
Ground fire	Flame of fire	1104
	Smoldering coals	964
Crown fire		1224

Intensity of emission of the i-th combustion product during a FF:

$$\Sigma\quad\frac{}{}\ \text{(kg/s)} \tag{23}$$

where:

k_i – emission coefficient of the i-th pollutant (table 5);

n – number of forest layers involved in the fire.

l – forest layers.

Table 5: *Values of pollutant emission coefficients during forest fires [8, 12]*

Name of the pollutant	Emission coefficient k_i
Carbon monoxide	0,113
Carbon dioxide	1,609
Nitrogen oxides	0,000405
soot	0,0062
Smoke (ultradispersed SiO_2 particles)	0,0345
methane	0,075
Unsaturated hydrocarbons	0,011
ozone	0,001

The calculation of the concentration of the i-th combustion product in a forest fire at ground level at a given distance x from the emission source in the wind direction is carried out on the basis of the Model of the distribution of concentrations of polluting particles in the atmosphere at a constant wind speed, described by the assumption of a double distribution in the Gauss equation:

$$(x \quad 0) \qquad \frac{\qquad}{} \qquad \left\{exp \quad \left[\frac{}{}\right]\right\} \ (\mathrm{kg/m^3}) \tag{24}$$

where:

U_a – average wind speed in the mixing layer (formula 29);

σ_y and σ_z – dispersion coefficients characterizing the scattering capacity of the atmosphere depending on the stability of the atmosphere.

For expressions of σ_y and σ_z, the Smith-Hosker formulas are currently used [13]:

$$(x) \qquad \frac{}{\sqrt{1}} \tag{25}$$

$$(x) \quad F(z \quad x) \cdot g(x) \tag{26}$$

$$F(z \quad x) \quad \begin{cases} \quad \left[c \qquad \left(1 \quad (c \qquad) \right)\right], \\ \ln \left| c \qquad \left(1 \quad (c \qquad)\right) \quad \right| x \end{cases} \tag{27}$$

$$g(x) \qquad \frac{\qquad}{} \tag{28}$$

where:

x – distance from the emission source, m;

z_0 – roughness height for different types of surface microrelief (Table 6).

Table 6: *Roughness height z_0 for different types of surface microrelief*

microrelief	z_0 , cm
Snow, lawn height 1 cm	0,1
Mown and low grass up to 15 cm	0,6-2
Tall grass up to 60 cm	4-9
Uneven surface with alternating patches of grass and shrubs	10-20
Park, forest up to 10m high	20-1000
City buildings	100

Table 7: *Values of parameters used in formulas for calculating σ_y and σ_z*

Atmosphere stability class	c_3	a_1	a_2	b_1	b_2
A	0,22	0,112	$5{,}38 \cdot 10^{-4}$	1,06	0,815
B	0,16	0,130	$6{,}52 \cdot 10^{-4}$	0,95	0,75
C	0,11	0,112	$9{,}05 \cdot 10^{-4}$	0,92	0,718
D	0,08	0,098	$1{,}35 \cdot 10^{-3}$	0,89	0,688
E	0,06	0,061	$1{,}96 \cdot 10^{-3}$	0,89	0,684
F	0,04	0,064	$1{,}36 \cdot 10^{-3}$	0,78	0,672

Table 8: *Values of parameters used in formulas for calculating σ_y and σ_z, depending on surface roughness*

Surface roughness, z_0, м	c_1	d_1	c_2	d_2
0,01	1,56	0,048	6,25·	0,45
0,04	2,02	0,027	7,76·	0,37
0,1	2,72	0	0·	0
0,4	5,16	-0,1	18,6·	-0,23
1,0	7,37	-0,096	4,29·	-0,60
4,0	1,7	-0,13	4,59·	-0,78

The average wind speed across the mixing layer is calculated using the formula [13]:

$$\left(\frac{}{}\right) \quad (\mathrm{m/s}) \qquad (29)$$

where:
z_1 – 10 m;
m – parameter depending on the class of atmospheric stability (table 12).

Table 9: *Values of parameter m for different classes of atmospheric stability*

Sustainability category	A	B	C	D	E	F
m	0,1	0,11	0,13	0,14	0,33	0,75

Social damage from forest fires is expressed in an increase in the overall mortality of the population, associated with intense and long-term smoke in urbanized areas.

Social damage from a forest fire is calculated using the formula:

$$\left\{\left(\frac{}{} \quad 005\right)+\left(\frac{}{} \quad 007\right)\right\}\frac{}{365\,(day)} \quad (\mathrm{rub}) \qquad (30)$$

where:
t_{inh} – inhalation time equal to forest burning time, days;
$C_{PM2.5}$ – PM2.5 concentration, μg/m^3 (formula 31);
C_{PM10} – PM10 concentration, μg/m^3 (formula 32);
C_{max10} – average daily maximum permissible concentration of suspended particles PM10, equal to 60 μg/m^3 [14];
$C_{max2.5}$ – average daily maximum permissible concentration of suspended particles PM2.5, equal to 35 μg/m^3 [14];
g_{PM10} – the amount of increase in PM10 concentration in the atmosphere of urbanized areas, equal to 10 μg/m^3, at which the average daily mortality rate of the population increases by 0,5%.
$g_{PM2.5}$ – the increase in PM2.5 concentration in the atmosphere of urbanized areas equal to 5 μg/m^3, at which the average daily mortality rate of the population increases by 0,7%.
$k_{a.m.}$ – the average annual mortality rate for the subject;
P is the population size in the urbanized area under consideration;
V is the cost estimate of the average statistical life, taken to be equal to 1 million rubles/person [15].

Based on the data on the share of fine fractions in total suspended particles (approximately 55% of PM10 and 65% of PM10 are PM2.5 particles) [16], the concentration of PM2.5 and PM10 is calculated:

$$(\mathrm{C} \qquad) \quad (\mathrm{mcg/m^3}) \qquad (31)$$

$$(C \qquad) \quad (\text{mcg/m}^3) \tag{32}$$

where:
C_C – concentration of soot particles (formula 24);
C_{SiO2} – concentration of ultrafine SiO_2 particles (formula 24).

III Testing

Calculations were made for Moscow for the period from August 1 to 12, 2010 (at the time of prolonged smoke pollution in the capital from large-scale forest and peat fires) using data on the areas of burned forests and peat bogs in the Moscow region in August 2010. The results obtained fully correlate with the data from monitoring the concentrations of suspended particles in the atmosphere and the Civil Registry Office data on mortality in August 2010 in Moscow. According to calculations, the average daily concentration of PM10 from August 1 to 12, 2010 was 550 μm/m^3 per day. According to "Air quality monitoring in Moscow, 2011", the average daily concentration of PM10 in the same period was 582 μg/m3. According to the Civil Registry Office of Moscow, the mortality rate in August was 15 016 people/month with an average mortality rate in the same period in other years of about 9 175 people/month (data from 2007 to 2019). The daily mortality rate in August 2010 in Moscow was about 484 people/day. In the calculations, the daily mortality rate was 493 people/day, a slight deviation from the registry office data can be explained by the previous jump in mortality in July, as well as a decrease in the concentration of fine particles in the air of Moscow in the second half of August due to a change in the weather as a result of the departure of the anticyclone.

IV Conclusions

Using this method allows us to take into account the steepness of the slope in the mountain-belt forests of Russia, which accordingly affects the speed of spreading the edge of the forest belt, as well as the thermal and physical characteristics of forest areas typical for the mountainous terrain of the Russian Federation.

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