Assessment of Carbon Dioxide Emissions due to Forest Fires in Russia and Possible Ways to Reduce Them

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Abstract. Calculations of CO2 emissions into the atmosphere caused by forest fires in Russia as well as an experimental assessment of some possibilities to reduce the emissions were carried out. It was shown that calculations with the usage of the average values of the reserves of combustible forest materials (CFM), the area of fires and the value of the mass rate of wood burning gives the same results as the approach based on the relatively accurate data on the reserves of CFM and their distribution over the fire area as well as an information on the character of forest fires. It was obtained experimentally that the continuous short-term supply of sprayed extinguishing liquid does not reduce but increases the yield of carbon dioxide due to the earlier termination of the flame burning and transition of the process to the smoldering regime. It is possible to reduce CO2 emissions into the atmosphere caused by forest fires up to 3-5 times when the extinguishing liquid is sprayed by applying two short-term pulses to eliminate both flaming and smoldering combustion.

1. Introduction

Russian forests account for 22 % of the world's forest reserves by area and more than 23 % by standing volume. The huge scale determines their key role in controlling CO2 emissions into the atmosphere. By providing a carbon sink of about 0.4 billion tons/year for many decades [1] they significantly reduce the impact of anthropogenic greenhouse gas emissions: according to official data [2], in 2018 total greenhouse gas emissions in Russia were estimated as 2.2 billion tons while taking into account the absorption capacity of forests changed this amount towards to 1.6 billion tons.

Forest reservoirs of biomass are responsible for two-thirds of the total potential to mitigate climate change [3,4]. However the ability of forest ecosystems to store carbon is under influence of some powerful factors such as productivity changes, climate extremes or forest fires. In contradiction with
existing global trend of declining damage caused by wildfires [5], the area, frequency and intensity of forest fires in Russia have increased over the past 20 years [6]: from 8000 to 20000 cases were detected annually in a period of 2001-2019 with an average burnt territory of more than 56 billion m²/year [7]. Obviously, CO2 emissions caused by forest fires significantly reduce the efficiency of forests as the carbon sink but known studies provide wide spread of estimations. It was concluded in [8] that an average annual direct flux of carbon dioxide from wildfire in Russia is about 0.05 billion tons with subsequent total post-fire CO2 emissions in the range from 0.12 to 0.28 billion tons annually. The value of 0.1 billion tons was obtained in [9] on the basis of satellite data as the value of the mean annual direct CO2 emission from forest fires, which is three times less than shown in [10]. As it follows from these numbers, wildfires in Russia reduce the ability of forests to absorb carbon dioxide by 11-43 %.

Moreover, it is necessary to have in mind that existing models predict that number of forest fires in Russian boreal zone is supposed to double by the end of this century followed by dramatic increase in the intensity of the events and related greenhouse gas emissions [11].

Based on the above, this paper attempts to continue the search to improve methods for assessing carbon dioxide emissions into the atmosphere caused by forest fires, in order to find further ways to reduce it when using fire fighting equipment.

2. Carbon dioxide emissions calculations

In the known estimation methods the mass of CO2 released in forest fires is determined through the mass of burning organic materials, that is, the calculation methods have the same basis. The mass of burnt forest materials depends on the area of the fire, the structure of the reserves of combustible forest materials (CFM) and their distribution over this area, the nature of the fire and its intensity [12,13]. The variety of conditions for the occurrence and development of wildfires, the differentiation in the composition and volume of CFM reserves and the different degree of involvement of forest tiers in the fire make almost impossible accurate assessment of the mass of burning materials. It is necessary to use approximate estimates based on different assumptions [14], which ultimately leads to a significant dispersion of data on carbon dioxide emissions into the atmosphere.

However, analyzing the data on the mass rate of burning of various forest combustible materials it is easy to see that the obtained values are close to the mass rate of burning of wood. It was shown [15] that for grass, fallen leaves, moss and lichen their mass burning rate \( m_b \) is in the range from 0.0075 to 0.022 kg·m\(^{-2}\)·s\(^{-1}\), accordingly, mean value is 0.0148 kg·m\(^{-2}\)·s\(^{-1}\). In [16], the value of the parameter \( m_b=0.0024 - 0.062\) kg·m\(^{-2}\)·s\(^{-1}\) was obtained for pine branches having a diameter of 5 mm and a length of 480 mm, depending on their humidity which varied from 0 % to 15 - 25 %. For the another form of wood samples more narrow range of the mass burning rates was obtained: \( m_b=0.004 - 0.0086\) kg·m\(^{-2}\)·s\(^{-1}\) [17], but the average value, which summarizes the results of a large number of studies on wood burning, is 0.015 kg·m\(^{-2}\)·s\(^{-1}\) [18], that is, it practically does not differ from the average value obtained in [1] for grass and fallen leaves.

If we use the same value of \( m_b=0.015\) kg·m\(^{-2}\)·s\(^{-1}\) for all types of fire load in the calculations, the intensity of CO2 emissions \( Q \) in kg·m\(^{-2}\)·s\(^{-1}\) is determined by the formula

\[
Q = C_{CO2} \cdot m_b
\]  

(1)

where \( C_{CO2} \) is the mass fraction of carbon dioxide released during the combustion of combustible forest materials. Its value was obtained in [19] for wood and paper in the range from 0.5 to 0.68 so it is equal to 0.59 as an average.

The mass of CO2 \( M_{CO2} \) released in a forest fire is calculated in accordance with the expression

\[
M_{CO2} = Q \cdot S_f \cdot t_f
\]  

(2)

where \( S_f \) is the area of fire and \( t_f \) is the time of burnout of combustible forest materials per m\(^2\).

The time of burnout depends from reserve of combustible forest materials \( m_r \) as
As it follows from [20] where thermophysical characteristics of the forest tiers are determined, \( m_i \) is equal to: 3.0 kg·m\(^{-2}\) for zero tier of the forest which is a tier of lichens, fallen needles, leaves and thin branches; 1.6 kg·m\(^{-2}\) for the first tier (grasses and shrubs, the height of the layer is about 2 m); 5.1 kg·m\(^{-2}\) for the second tier (so called undergrowth which is a combination of young trees having a height of 6 m or less); 5.1 kg·m\(^{-2}\) for the third tier (tree crowns with the height of 22 m).

The CFM reserve for all the listed forest tiers will be \( m_i = 14.8 \text{ kg·m}^{-2}\). Than according to (3) we obtain \( t_f = 14.8/0.015 = 986.7 \text{ s} \approx 16.4 \text{ min} \).

Official data from FBU Avialesokhrana shows that the total area of forest fires in Russia in 2020 was \( S_f = 9227679.19 \times 10^4 \text{ m}^2 \) which is 114 % more than the average area of forest fires in the period from 2006 to 2015 [9]. Therefore, using the formulas (1) and (2) for the scenario of complete burning of all forest tiers, we obtain the mass of CO2 emitted as a result of forest fires in Russia in 2020 \( M_{\text{CO2}} = 0.59 \times 0.015 \times 9227679.19 \times 10^4 \times 986.7 \approx 805.8 \times 10^6 \text{ kg} \).

With the same assumptions for the average value of the area of forest fires \( S_f = 4.31 \times 10^4 \text{ m}^2 \) [9] total emissions of CO2 are equal to \( M_{\text{CO2}} = 376.4 \times 10^6 \text{ kg} \) for the period from 2006 to 2015. This amount represents the highest estimation of the emissions which is 3.76 times bigger than the value obtained in [9] without taking into account the burnout of the zero tier of the forest and 66.8 % more than the value obtained in [10]. But becomes closer to the results of [10] when we consider that 98 % of forest fires are grass-roots fires [20] and do not affect the third tier of the forest. The CFM reserve in this case is \( m_i = 9.7 \text{ kg·m}^{-2}\), accordingly, \( t_f = 9.7/0.015 = 646.7 \text{ s} \) and the total CO2 emissions are equal to \( M_{\text{CO2}} = 246.7 \times 10^6 \text{ kg} \) which is only 9.3 % more than the estimate made in [10].

It should be emphasized once again that this paper and articles [9,10] apply the same methodology, but in our work averaged values are used while relatively accurate data on the reserves of CFM and their distribution over the fire area as well as an information on the character of forest fires are involved into consideration in [9,10].

3. Experimental technique

As it follows from (1), (2) and (3), carbon dioxide emissions caused by forest fires can be reduced by influencing the mass fraction of CO2 released during the combustion of CFM, the area of fire and the time of burnout of CFM. This paper shows the results of an experimental study of the effect of extinguishing combustible forest materials with water and 10 % aqueous solutions of bischofite, OS5 based on diammmonium phosphate, prospective flame retardant containing phosphates and AFFF foaming agent on the value of \( C_{\text{CO2}} \).

The experiments were carried out at a set-up presented in figure 1. The main element of the set-up is gas analyzer Test 1 which technical characteristics are shown in Table 1.

| Detectable component | Measuring range | Measurement accuracy | Device performance |
|----------------------|-----------------|----------------------|--------------------|
| O2                   | 0 – 25 % vol.   | ±0.2 % vol.          | ≤15 s              |
| H2                   | 0 – 5 % vol.    | ±0.2 % vol.          | ≤35 s              |
| CO2                  | 0 – 30 % vol.   | ±2 %                 | ≤25 s              |
| CH4                  | 0 – 30 % vol.   | ±5 %                 | ≤25 s              |
| CO                   | 0 – 40000 ppm   | ±5 %                 | ≤35 s              |
| NO                   | 0 – 1000 ppm    | ±5 %                 | ≤35 s              |
| NO2                  | 0 – 500 ppm     | ±7 %                 | ≤45 s              |
| H2S                  | 0 – 500 ppm     | ±7 %                 | ≤45 s              |
| SO2                  | 0 – 1000 ppm    | ±5 %                 | ≤45 s              |
Test 1 takes a gas probe via a sampler and detects various components of the gas mixture. The sampler was installed at a height of 20 cm above the surface of the CFM in the model fire source.

The experimental investigation of combustion of fallen leaves, needles and pine bars was conducted at ambient room temperature. Two types of a model fire source were used. For the experiments with foliage and needles a special stainless steel holder having equidistant holes on its surface (side and bottom) for air circulation was developed. Before the experiment the holder was filled with combustible forest material (foliage, needles) weighing 0.1 kg; after that the CFM was ignited. In the experiments with pine bars having a length of 120 mm and a cross section of 15x15 mm they were laid out in a cubic three-row stack. After the stack was arranged on a solid support (steel corners) it was set on fire.

![Figure 1. Experimental stand.](image)

A system consisting of a cylinder with a fire extinguishing liquid under a pressure of 200 kPa, a channel for its supply and a spray nozzle was used to generate a drip flow of the sprayed liquid. The spray times until complete suppression of the flame were in the range from 5 to 8 seconds depending on the composition of fire suppressant.

4. Results and discussion
Figure 2 shows the concentration fields of CO2 and CO formed during the burning of various types of CFM in absence of extinguishing.

![Figure 2. Content of CO2 and CO in a smoke formed during the burning of CFM. 1- pine bars; 2 – foliage; 3 – needles.](image)
It was found in the experiments that the main gaseous products of CFM combustion are CO2, CO and NO, the concentrations of which vary in the ranges 1.0–13%, 0.1–3.9% and 20-220 ppm, respectively. The greatest amounts of CO, CO2 and NO are released during the pyrolysis of needles.

Figures 3 and 4 show the values of the concentrations of carbon-containing gases formed during the extinguishing of pine bars or needles by continuous and pulsed supply of various liquid fire suppressants. The points in Figure 3 indicate the time when the fire extinguishing agent starts spraying. After 5-8 seconds the spraying was stopped due to elimination of flaming and absence of repeated fires.

It is easy to see from the data in Figure 3 that the continuous short-term supply of the extinguishing liquid does not reduce but increases the yield of carbon dioxide or carbon monoxide due to the earlier termination of the flame burning and the transition of the process to the smoldering regime.

![Figure 3. Content of CO2 and CO in a smoke for continuous supply of fire extinguishing liquid to suppress combustion of pine bars.](image)

Such an effect is absent when the extinguishing liquid is sprayed by applying two pulses of 2-3 seconds each, as follows from the data presented in Figure 4.

![Figure 4. Content of CO2 and CO in a smoke for pulsed supply of fire extinguishing liquid to suppress combustion of needles.](image)

The experiment shows that two pulses delivered after 38 and 68 seconds from the moment of ignition of the model fire source are sufficient to eliminate both flaming and smoldering combustion. As a result, the value of $C_{CO2}$ decreases by a factor of 3-5 which means a corresponding reduction in carbon dioxide emissions into the atmosphere.
5. Conclusions
It was shown that calculations of CO2 emissions into the atmosphere due to forest fires in Russia with the usage of the average values of the reserves of combustible forest materials, the area of fires and the mass rate of wood burning gives the same results as the approach based on the relatively accurate data on the reserves of CFM and their distribution over the fire area as well as an information on the character of forest fires.

Carbon dioxide emissions caused by forest fires can be reduced by influencing the mass fraction of CO2 released during the combustion of CFM, the area of fire and the time of burnout of CFM.

It was obtained experimentally that the continuous short-term supply of sprayed extinguishing liquid does not reduce but increases the yield of carbon dioxide due to the earlier termination of the flame burning and the transition of the process to the smoldering regime. In contradiction with this, it is possible to reduce carbon dioxide emissions into the atmosphere caused by forest fires up to 3-5 times when the extinguishing liquid is sprayed by applying two short-term pulses to eliminate both flaming and smoldering combustion.

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