Physicochemical properties in the post-pyrogenic soils from the forests of Central Russia

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Abstract. The paper deals with an eight years monitoring of physicochemical properties of leached chernozem from mixed and broad-leaved forest of the Lipetsk region of European Russia exposed to large-scale fire in 2010. It was revealed that in 2011 the year following the forest fire, the soil had higher pH (7.21 in mixed forest compared to 6.01 of reference soil) and lower hydrolytic acidity, which decreased from 2.69 (reference soil) up to 0 [mmol(eq)/100 g of soil] compared to 2010. Due to fire, the humus content and exchangeable cations concentration decreased, particularly, from 6.08 up to 4.43 % and from 39.2 up to 37.6 [mmol(eq)/100 g of soil]. Since in the period from 2011 to 2017 there was a drop in the content of alkaline-hydrogenated nitrogen (N_{alk-hyd}) (from 24.1 up to 18.2), we found an increase in the content of mobile compounds P_{2}O_{5} (from 7.78 (reference soil) up to 8.72). The content of exchangeable potassium (K_{2}O) went up from 18.5 up to 19.2 in 2011, compared to the reference areas.

1. Introduction

Russia as well as the USA, Canada, Portugal, Spain and Australia, are among the countries, which forests are regularly exposed to fires [1, 2]. Forest fires affect ecosystems in a holistic manner and they can have both positive and negative effects. Despite of the increasing anthropogenic pressures in previous decades, hot temperature in warm season is still major factor causing frequent forest fires. Besides, there are more fires due to climate changes – «heat waves» leading to droughts [3, 4].

Cardinal difference influencing of pyrogenic factor on the forming and development of forests growing in various zone-geographical conditions is reviewed. Forestry-ecological features of preventive controllable burning of combustible materials in areas covered and non-covered with forest for the purpose of decrease fire risk are considered [5].

Green Belt of trees with the nearest forests in the Lipetsk region (Russia) nearby the city forms a coherent and extensive urban landscaping system. Hot dry summer in 2010 caused a forest fire that covered large forest area of the Lipetsk region that significantly affected forest biogeocoenosis and damaged tree stand, undergrowth, underbrush, and living top soil.

The restoration of soils after a fire mainly depends on fire duration type and intensity as well as from the type of forest. The leading Russian scientist Prof. Ivan Melekhov noted that the main diagnostic features of fire and post-fire consequences were the height of trunks deposit, the degree of forest litter burning, and fire damage of living topsoil [1].
Postfire transformation of soils was studied by many authors [4-6]. It was noted that fires significantly changed physicochemical properties, particle size distribution, the water-air and hydrothermal modes of soils, and also there is a change of quantity and stability of the organic matter that has a direct impact on the biological properties of the soils. In the literature there is information about the impact of the fire on the eastern part of Russia, but data on change of a soil cover in the European part of Russia are absent [6]. Therefore, the study of the impact of forest fires on the soil cover of the Lipetsk region is very important.

The purpose of our work was to monitor physicochemical properties of the soils within eight years period after a forest fire.

2. Materials and methods

The object of the study was leached chernozem characterized as medium-humus, medium-thick, surface of carbonate loam, located in the Zadonsky district of the Lipetsk region near the settlement of Kashary (n.l. 52°30’37.3” e.l. 38°57’28.7’’). The samples of chernozem were compared to reference soil – the soil of the same composition and basic properties taken from the Zadonsky district of the Lipetsk region the area which was not affected by forest fire (n.l. 52°30’40.0” e.l. 38°57’31.6”, GPS Navigator Garmin Oregon 750 2017, Taiwan, China).

Soil samples were selected in 2011-2017 in the territory exposed to pyrogenic effects in 2010. It was laid 9 soil sections under the mixed forest and 9 in broad-leaved forest (in triplicate repetition). From the soil sections the selection was carried out layer by layer to a depth of 40-50 cm. In addition, on to reference soils that were not attacked by pyrogenic exposure, there were made 2 full-profile soil sections (under the mixed forest and under broad-leaved forest), revealing the soil-forming rock (in triplicate repetition) [7].

In the samples we measured $\text{pH}_{\text{H2O}}$ and hydrolytic acidity, $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ content, total humus, nitrogen of easily hydrolyzable compounds, soluble phosphates, and exchange potassium parameters according to [8-10].

$pH_{H2O}$ was determined by on the potentiometer. Analysis $pH_{H2O}$ of the water extract was prepared in the ratio soil: water 1:2.5. The method is based on measuring the voltage across the electrodes of the electrochemical cell in the absence of current. It measures the activity of hydrogen ions in solution, using a glass display electrode. It consists of a case filled with a buffer solution. $H^+$-ions, in solution, can get into the emptiness of a silicate framework of a glass ball. Thus, there is an electrode potential in process of which increase the electrochemical balance is established, interfering further penetration of $H^+$-ions inside the electrode. In consequence of this, the activity of $H^+$ in internal solution remains to a constant and the potential of an electrode depends only on activity of $H^+$ in solution. Glass pH-electrodes are most effective in the field of $pH$ 1-10. At measurement of $pH$ the indicator (glass) electrode has to be sustained for at least 8-10 h in 0.1 N HCl, and then several times carefully washed with the distilled water. The electrode of comparison is filled with KCl solution according to the manual instruction and then kept for several hours in the distilled water at 25°C. Adjust an ionomer on solution with pH close to neutral 6.86...7.01 (Akvadistilloyator DE-25M EMO, 2016, Plant, St. Petersburg Russia, Electronic scales DEMCOM DL-312 (max 310 g, ±0.01g), 2017, Russia, pH/ion meter S500 Seven Excellence S500-Fluoride, 2017, USA). Hydrolytic acidity of the soil was estimated by Kappen, in the interaction of $\text{CH}_3\text{COONa}$ with the soil at pH 8.2. The acetic acid was titrated with 0.1 N NaOH with the indicator phenolphthalein. According to the number needed to titrate NaOH solution calculated total hydrolytic acidity. Internationally, when determining the total acidity potential instead of $\text{CH}_3\text{COONa}$ solution, a solution containing BaCl₂ and triethanolamine with pH 8.2 used.

The content of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ was measured by the Gedroits complexonometric method in non-carbonate soils in their decantation replacement prior to complexometric determination and displace them from the soils with 1 N NaCl. The degree of saturation of soil bases is calculated according to the equation $V = 100\% \frac{S}{(S+H)}$, where $V$ – the degree of saturation, $S$ – sum of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$, $H$ – total hydrolytic soil acidity. Total humus was measured according to Tyurin in the modification of
Simakov. The method is based on the oxidation of carbon of humic substances up to 0.4 N CO₂, K₂Cr₂O₇, prepared on 0.6 N H₂SO₄ (Electric tile infrared 2016 Russia). The remainder of the chromium mixture, which did not go for carbon oxidation of organic carbon, its quantity was judged. The residue of H₂CrO₄, that did not consumed in oxidation, titrated with 0.1 N (NH₄)₂(SO₄)₆H₂O with indicator (C₆H₅)₂N. Nitrogen of easily hydrolysable compounds in an alkaline extract (Nₐlk-hyd) according to Cornfield. The method was based on the hydrolysis of organic compounds of the soil by 1 N NaOH. The ammonia released during this process was taken into account by the microdiffusion method with use of the modified cast cups of Conway. Besides the ammonia, which is formed during the hydrolysis of soil organic matter, the method took into account exchangeable ammonium. Ammonia at the same time is absorbed by solution of 0.06 N H₃BO₃ and titrated with 0.02 N H₂SO₄.

Soluble phosphates P₂O₅ were detected by photocolorimetric determination after the interaction with 600 at 750 nm on spectrophotometer (Photometer flame PFA 378 2015 Russia). K₂O in non-carbonate soils was estimated with a flame photometric termination based on the extraction of mobile phosphorus and potassium from the soil by 2 N CH₃COOH and subsequent determination of P₂O₅ in the form of a blue phosphorus-molybdenum complex on the photoelectric colorimeter (Photocolorimeter KFK-3KM, Russia) and K₂O – on an a flame photometer with 766 at 770 nm (Photometer flame PFA 378, 2015, Russia) [11]. The obtained data were variationally statistically processed using Stadia and Microsoft Excel programs.

3. Results and discussion

According to Dr. Alexey Dymov, the fires lead to a redistribution of organic matter concentrated in the soil between the litter and top mineral horizons. In soils of the post-pyrogenic landscapes there is a 2-8-fold increase in the content of polycyclic aromatic hydrocarbons. In the soils of ecosystems, passed by fires happened 100-150 years before, their content decreases to conditionally reference soil values. The proportion of aromatic fragments increases in the composition of light fractions of organic matter. In the first years after the fires the carbon content of water-soluble organic compounds in the pyrogenic horizons decreases from 3 to 27 times compared with the organogenic soil horizons of the conditionally reference soil [1].

After a forest fire, there are created certain physicochemical conditions causing acidity fluctuations with a drop in the first year after a forest fire, and an aeration and dryness increase of the soil [12]. In the case of the fire on the surface of the topsoil, the temperature reaches up to 940…960°C, under the topsoil it already decreases to 50°C, and at a depth of 10 cm it increases by only 2…3°C, which is confirmed by the data of Dr T. Louis [13]. Due to high moisture and reduced thermal impact on the soil, forest litter is an essential buffer, protecting the soil from high temperatures.

Analysis pH₂O of the water extract showed that after a fire in the pyrogenic section in the 0-10 cm layer of leached chernozem located under the subordinate and broadleaf forest, there was observed a change in the reaction of the medium toward alkalization, which was due to the penetration of ash soluble water compounds into the soil, saturating the absorbing complex with alkaline-earth elements and causing a shift in the reaction. In the following years, after a forest fire, it was observed that there is a tendency of pH₂O to the reference soil (table 1, figure 1).

Table 1. Statistical indicators of physicochemical properties in reference soils.

| Depth, cm | n  | pH₂O | H⁺ | Ca²⁺+Mg²⁺ |
|-----------|----|------|----|-----------|
|           |    |      |    | [mmol (eq) / 100 g of soil] |
| 0-10      | 3  | 6.01±0.32 | 2.69±0.62 | 39.2±0.52 |
|           |    | Leached chernozem (mixed forest) |
| 0-10      | 3  | 6.47±0.29 | 1.45±1.02 | 40.6±1.27 |
|           |    | Leached chernozem (broad-leaved forest) |

Note: n is a number of samples; x̄ is an arithmetical mean; x̄ ± sx is an arithmetical mean with a mistake of an arithmetical mean.
In 2011 there was observed that the hydrolytic acidity in the leached chernozem under both mixed and broad-leaved forest decreased, especially in the upper layers of the soil profile (where it was not found), compared to the reference soil, the hydrolytic acidity content under the mixed forest is 2.69 mmol (eq) / 100 g of soil and 1.45 mmol (eq) / 100 g of soil under the broad-leaved forest. In 2012 the hydrolytic acidity became 1.27 and 0.39 [mmol (eq) / 100 g soil] under the mixed and broad-leaved forest, respectively. In 2017, the hydrolytic acidity increased by 20.1% under the mixed forest (1.59 [mmol / eq / 100 g soil]) compared to 2012 and by 33.9% (0.59 [mmol / eq) / 100 g soil]) under broad-leaved forest and the aspiration of their values to the reference soil. Thus, the soil as an open system tends to have the original indicators of the original internal structure (figure 2) [14].

In 2011 the content of Ca\(^{2+}\) and Mg\(^{2+}\) in 0-10 cm layer went down by 4.08 and 4.68% under the mixed and broad-leaved forest, respectively. The result is explained by the transition of part of Ca\(^{2+}\) and Mg\(^{2+}\) to the insoluble form of CaCO\(_3\). In subsequent years followed by the fire, the content of Ca\(^{2+}\) and Mg\(^{2+}\) did not change significantly in 0-10 cm layer of the chernozem compared to the first year, after the fire in 2012 it was 37.4 in mixed and 38.5 [mmol (eq) / 100 g of soil] in broad-leaved forest, while in 2017 it reached 37.6 and 38.7 [mmol (eq) / 100 g of soil], respectively (figure 3).

The degree of saturation of the soils in the year after the forest fire, under mixed forest increased by 7.2% in the upper layer 0-10 cm and under broad-leaved forest by 3.7%, due to a reduction in hydrolytic acidity. In the following years, we observe a decrease in this indicator, which is caused by the decrease in hydrolytic acidity (in 2012 it decreased by 3.3% relative to the first year under mixed forest, by 1.0% in broad-leaved forest, and by 4% and 1.7% in 2017, respectively).

According to prof. Yuri Krasnoshchekov, one of the main sources of organic matter and ash elements entering the soil is the forest litter. The wide variability of litter stocks and their chemical composition is known due to the typological variety of plantations, the structure of stands, differences in the physical and geographical conditions of the environment. Under the influence of forest fires, especially grass-roots fires, occurs partial or complete combustion of litter, which subsequently affects the properties of soils, especially their upper horizons [15]. In leached chernozem under mixed forest and under broad-leaved forest that had exposed to forest fire in 2011, The humus content decreased from 6.08 (reference soil) up to 4.43% (pyrogenic areas) in mixed forest, the loss of humus content changed 6.40 (reference soil) up to 4.92% (pyrogenic areas). In 2017, there were losses of organic matter in the 0-10 cm layer of the soils mixed forest and broad-leaved forest by within the deviation...
compared to the reference soil values, which is due to the direct destruction of organic matter under the influence of high temperatures (table 2, figure 4).

**Table 2.** Statistical indicators of chemical properties in reference soils.

| Depth, cm | n  | Humus, % | N $\bar{x} \pm s_x$, mg/100 g soil | P$_2$O$_5$ $\bar{x} \pm s_x$, mg/100 g soil | K$_2$O $\bar{x} \pm s_x$, mg/100 g soil |
|-----------|----|----------|------------------------------------|---------------------------------------------|-------------------------------------|
|           |    |          | Leached chernozem (mixed forest)    |                                             | Leached chernozem (broad-leaved forest) |
| 0-10      | 3$^1$ | 6.08±0.56 | 7.78±0.58                          | 18.5±1.41                                  | 18.7±1.67                           |

Note: $n^1$ is a number of samples; $x^2$ is an arithmetical mean; $\bar{x} \pm s_x$ is an arithmetical mean with a mistake of an arithmetical mean.

In 2011 year the content of N$_{alk-hyd}$ under mixed forest in the 0-10 cm layer decreased from 24.1 (reference soil) to 18.2 (mixed forest) [mg / 100 g soil], and under broad-leaved forest from 25.4 to 18.6 [mg / 100 g of soil]. In 2017, the content of N$_{alk-hyd}$ in the investigated pyrogenic soils decreased by an average of 30.7% compared to the reference soil, due to the fact that at temperatures around 500° C most of the organic nitrogen compounds burn (figure 5).

In the leached chernozem under mixed forest, the content of mobile compounds P$_2$O$_5$ increased up from 7.78 (reference soil) up to 8.72 [mg / 100 g soil] in 2011, and under broad-leaved forest from 8.56 to 9.54 [mg/100 g of soil]. In 2017, the content of mobile phosphorus compounds in leached chernozem under mixed forest increased to 9.15, under broad-leaved forest to 9.85 [mg / 100 g of soil] (by 17.6% and 15.1%, respectively). After exposure of the pyrogenic factor, takes place alkalinization of the soil solution and, as a consequence, an increase in the content of mobile phosphorus compounds in the 0-10 cm soil layer due to their high content in the ash formed after the forest fire [14] (figure 6).

In 2011 the content of K$_2$O in leached chernozem under mixed forest increased from 18.5 (reference soil) up to 19.2 [mg / 100 g of soil] and under broad-leaved forest from 18.7 to 19.5 [mg / 100 g of soil]. Content of K$_2$O in the following years after the pyrogenic effect stabilized compared with 2011, when the value of this indicator under mixed forest and broad-leaved forest increased by an average of 4.03% (figure 7).

![Figure 3. Dynamics of the Ca$^{2+}$+Mg$^{2+}$ in leached chernozem (0-10 cm), mmol (eq) / 100 g of soil.](image)

![Figure 4. Dynamics of Humus in leached chernozem (0-10 cm), %](image)
Prof. Sergey Bazha described the state of vegetation and soil cover in the Barguzin hollow in connection with the desiccation of soils, formed as a result of a 3-year drought and resulted in the death of natural pine forests and forest belts of pine and poplar balsamic. He identified the main causes of death of woody vegetation, as well as soil conditions, which provided its survival in the long-term atmospheric drought. He came to conclusion about the negative trend of development of forest-steppes in the aridization of the climate of the Northern Baikal region [16].

4. Conclusion
Studies of the dynamics of the six-year change in the physicochemical properties of the soil under the influence of a forest fire showed that in 2011 after the pyrogenic effects in forest soils, there is a reduction in the content of organic matter and N_{alk-hyd} in the upper layers of soil in the 0-10 cm, which is connected direct with their destruction because of a high temperatures (combustion).

After pyrogenic exposure, the content of the ash elements P_{2O_5} and K_{2O} increases. It was revealed the tendency to increase of pH_{H_2O} values and decrease of hydrolytic acidity in soils after forest fire. The pyrogenic factor influenced the content of Ca^{2+} and Mg^{2+}, toward their decrease, which is associated with a decrease in the humus content. In 2017, we observe the tendency of returning pH_{H_2O} to the reference soil. Hydrolytic acidity increases, the degree of saturation of soils with bases decreases, thereby emphasizing that the soil as an open system tends to the initial indicators of the original internal structure.

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