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Research Article

THE IMPACT OF MODERN CLIMATE CHANGE AND SOIL POLLUTION ON THE FUNCTIONING AND THE STATE OF AGROECOSYSTEMS IN THE BAIKAL SIBERIA

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A B S T R A C T

Monitoring (1997-2012) was focused on the impact of gray forest soils (Luvic Greyzemic Phaeozems) pollution with aluminum industry fluorides on carbon transformation and agroecosystems functioning at the background of present day climatic changes. Air temperature increase compared to «climatic norm» (1961-1990) was found to closely correlate with CO_2 emission, but not to affect soil microbe biomass carbon content (Cmic). Systemic analysis of carbon transformation consequences demonstrated negative influence of fluorides on carbon flow integrated agroecosystem components (soil-microorganisms-plants-atmosphere), particularly in anomalous years. The regimes of agroecosystems functioning and its environmental loads were evaluated by the proportion of flows of net-mineralized and (re)immobilized (N-M:RI) carbon.

INTRODUCTION

Current climate changes, as well as technogenic pollution of the environment, act as a basis of evaluation of their impact on status and stability of surface ecosystems. Their biospheric functions linked with the formation of carbon cycles are profoundly studied (Dobrovol'skii *et al*., 2000; Mokhov, 2006; Zavarzin *et al*., 2006 *et al*.). Of particular interest is the enhancement of CO_2 emission as carbon flow to atmosphere contributing to climate warming. The problem of contemporary climatic changes is constantly discussed in the reports of Intergovernmental expert group (IGEG), in the Russian Committee on Hydrometeorology (ROSGIDROMET) reports and other publications (Kudeyarov et. al., 2005; Mokhov, 2006; Zamolodchikov, 2013). The existing concept of climate warming and increasing impact of anthropogenic factors are critical for the research. The necessity of taking into account of not only industrial CO_2 emission into the atmosphere, but also of carbon flow from soils, formation of which differs in surface ecosystems of different natural-climatic zones. The existing analyses of soil respiration in the territory of Russia consider the role of multiple factors в (Gruza *et al*., 2002; Kudeyarov *et al*., 2005; Kurganova, 2011). For example, in Baikal region forest-steppe in agroecosystems on technogenic polluted soils there was identified increased mineralization of organic matter, which is accompanied by enhancement of CO_2 emission into the atmosphere and decrease of (re)immobilization of carbon by soil microbe biomass. This causes negative changes in the formation of intra-soil carbon cycle, which affect reduction of arable soils resource potential and resistance of agroecosystems (Pomazkina, 2004, 2011; Pomazkina *et al*., 2013). Acquisition of objective information and overviews of environmental changes in concrete natural-climatic regions, may be ensured only by long-term monitoring.

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The study was aimed at the monitoring (1997-2012), which at the background of annual climatic changes identified the impact of technogenic fluoride pollution on microbial transformation of carbon and agroecosystem functioning on gray forest soils *(Luvic Greyzemic Phaeozems)* of Baikal Siberia.

Research Method and Object

The monitoring (1997-2012) was conducted in the station (52°14'N and 104°16'E) in the zone of Baikal Siberia forest-steppe. Evaluation of spatial-temporary carbon transformation in changing environmental conditions was based on observations in agroecosystems of intensive crop rotation (fallow-first year wheat-second year wheat). Field tests were performed on gray forest medium-loamy soil – both non-polluted and technogenic polluted with fluorides (D and DF respectively). Polluted soil from impact zone of Irkutsk aluminum smelter was transported to the station, which allowed to «eliminate» uncontrolled fluoride pollution. At the experimental site after removal of humus layer within carcasses limiting allotment area there was formed arable layer of the polluted soil. Simultaneously conducted field tests on non-polluted soil of the station were used as control. The number of allotments corresponded to the number of variants of intense crop rotation, with 3-4 repetitions. The study was designed to ensure representative selection of soil samples for comparative analysis. The article presents annual results characterizing carbon transformation in agroecosystems with spring wheat sown after fallow.

Soil physical and chemical properties were analyzed by generally accepted methods (Agrochemical methods…, 1975). Content of overall and water-soluble fluorides in soil was determined by spectrophotometry (Dmitriev *et al*., 1989). The degree of mobility (DM) of fluorides was assessed as F_{water} /$F_{overall}$, %, and buffer qualities in respect of fluoride pollution (B_{NaF}) were calculated on the basis of soil properties (Pomazkina *et al*., 2004):

$$B_{NaF} = [C_{org} \times (C_{ha}:C_{fa}) \times CEC] / (Na_{exch} \times DM)$$

Annual monitoring of hydrothermal parameters included determination of air temperature, precipitation amount, and the soil water content. Accompanying dynamic measurements of C-CO_2 emissions from soils and carbon content in soil microbe biomass (C mic) were carried out in the format of operative monitoring (April-October, interval 7-15 days). C mic was determined by the rehydration method (Blagodatskii *et al*., 1987), optimal for field tests. Parameters for vegetation were calculated as arithmetic mean. Average daily speed of CO_2 emission from soils was determined by absorption method (Sharkov, 1986) using Infralit-4 analyzer for control measurements (Pomazkina *et al*., 1996). Annual parameters were used for evaluation of overall CO_2 emission during a month, vegetation, inter-seasonal period and a year.

Test results were summarized by systemic and comparative analysis, which revealed peculiarities of agroecosystems functioning in changing environmental conditions (Pomazkina, 2004, 2011 *et al*.). Agroecosystem was studied as an open system of interacting components (soil-microorganisms-plants-atmosphere), which are integrated by carbon flows characterizing exchange inside, between the components and with the environment. Mineralized carbon (M) was considered as «entrance» of the substance into the system, which forms two flows: net-mineralized (N-M – «exit») and (re)immobilized (RI) – «return at the exit» (feedback) providing formation in the soil of active pool of newly formed carbon-containing matters. The impact of environmental factors (load) on the regime of agroecosystem functioning was assessed on the basis of carbon transformation in intra-soil cycle (mineralization ↔ (re)immobilization). Mineralized carbon was calculated as the sum, which in total included its content in soil microbe biomass (C mic) and the flow of C-CO_2 emission (net-mineralized carbon). The formation of flow of (re)immobilized carbon was connected with processes of carbon microbe immobilization and re-synthesis. Average vegetation carbon flow value (g C/m^2) was calculated with arable soil layer density taken into account.

Experimentally found proportion of flows of net-mineralized and (re)immobilized carbon (N-M:RI), as well as evaluation of RI carbon flow in respect of that mineralized over the vegetation (RI:M, %) are used for integral assessment of the regime of agroecosystem functioning. The scale of assessment criteria was developed (Table 1). Dynamically equilibrium condition of agroecosystem of homeostasis regime characterizes compensation of flows (N-M:RI). With the increase of the load on agroecosystem the functioning regime changes: stress, resistance, adaptive depletion, and repression. The approach has been tested in several other works by the author (Pomazkina, 2015; Pomazkina *et al*., 2013). The efficiency of its application for summarizing results of long-term monitoring studies is accounted for by the necessity of integral evaluation of simultaneous impact on the agroecosystem of hydrothermal conditions and soil technogenic pollution.

Table 1 Criteria of the regimes of functioning of an agroecosystem and corresponding loads on it

Functioning regime	Load	Criteria	
		RI:M, %*	NM:RI*
Homeostasis	Norm	50-45	0.8-1.2
Stress	Permissible	45-35	1.2-2.0
Resistance	Maximum permissible	35-25	2.0-3.0
Adaptive depletion	Critical	25-15	3.0-5.0
Repression	Impermissible	<10-15	>5.0

*Symbols in the text

Statistical processing of the data was carried out with the software package Excel 2007 for Windows.

RESULTS AND DISCUSSIONS

Characteristics of climatic conditions. Baikal region forest-steppe is characterized by contrast average daily and seasonal air temperatures. Non-frost period lasts 75-110 days. Average July temperature is 17-18^oC. Temperature sum over 10^oC is low (1595^oC). Spring and summer frosts are possible. Annual precipitation amounts to 270 - 386 mm, with maximum (80-90 %) falling on warm period. Early summer may be droughty. Agricultural conditions are classed as extreme (Agroclimatic Reference Book..., 1962).

Global climate warming is known to have accelerated in the last few decades. Thus, according to ROSGIDROMET data, the changes are most salient in southern regions of East-Siberian region. Temperature sum over 10^oC has increased by 94^oC on average. Maximal increase was registered in July (by 1-1.2^oC). Summer precipitation decreased.

According to the Ikutsk weather station (All-Russia Institute of Hydrometeorological Information; http://www.meteo.ru) located in the vicinity of the monitoring zone, in keeping with the requirements of World Meteorological Organization (WMO, 2008), over the vegetation period 1961-1990, there was estimated «climatic norm» of hydrothermal parameters, which was used as a reference for deviations of average daily air temperature and precipitation total in the years of the monitoring (1997-2012). Average temperature in most years of the monitoring was found (Fig.1) to exceed the climatic norm (x) by over 2 σ, the precipitation total was within the norm, and the Selyaninov hydrothermic coefficient (HTC) corresponded to the gradation sufficient or optimal moisture availability (Zoidze and Khomyakova, 2006). 2002 demonstrated maximum deviation from the norm, as it was characterized by high air temperature, low precipitation total and insufficient moisture availability. 2004 was closer to the norm in terms of air temperature, but had higher precipitation rate, and HTC showed excessive moisture availability. These two years were considered anomalous.

Comparative analysis of the impact of climatic indices on carbon microbe transformation in agroecosystems was based on the indices obtained in 1997, 2002, 2004 and 2010. 1997 was close to the norm, with average vegetation period air temperature amounting to 15.5°C, precipitation total - to 266 mm, and HTC - 1.66 (optimal moisture availability). In 2002 air temperature was high (16.9°C), precipitation total was lower (170 mm), and HTC (0.92) characterized low moisture availability. In 2004 the temperature was closer to the norm (14.8°C), precipitation total reached its maximum (434 mm), with HTC amounting to 2.25. 2010 parameters amounted to the following values respectively: 14.8°C, 272 mm, HTC 1.44 (excessive moisture availability).

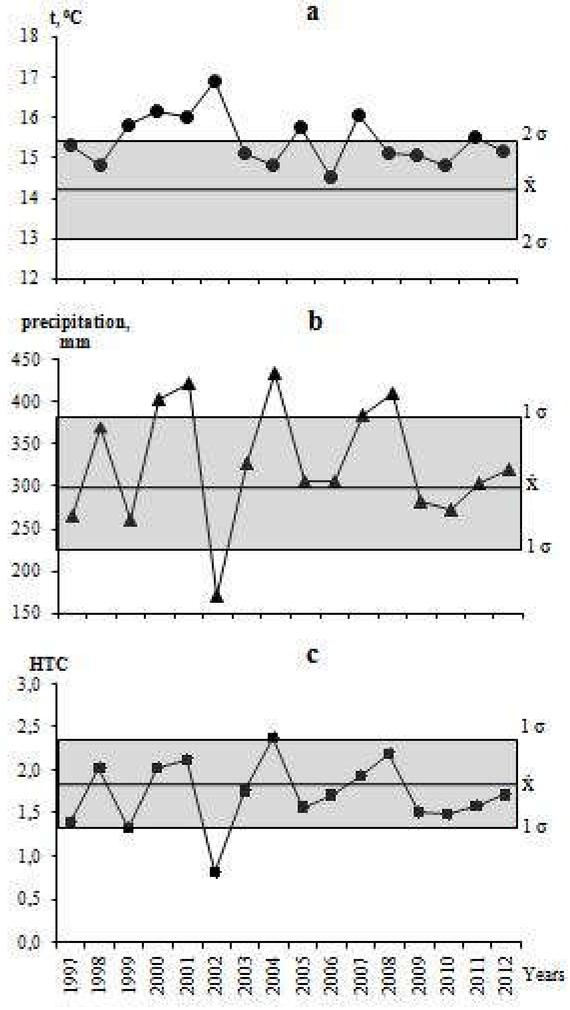

Fig 1 Deviation of the air temperature (a), precipitation (b) and hydrotermic coefficient (c) from the climatic norm (x̄) calculated for the growing seasons of the monitoring period.

Soil properties characteristics. Soils under study are gray forest medium loamy soils – unpolluted variety (D) and technogenically polluted variety (DF) – differed in qualities, which mostly depended on the content of water-soluble fluorides in arable layer (Table 2). At the beginning of the monitoring in DF soil pollution attained 6 MPC (the maximum allowable concentration of 10 mg/kg (Sanitary Normatives, 1987)), and degree of mobility (SP) fluorides reached 7.0 %. Alkalinization and salinization of DF soil resulted from sodium fluoride accumulation due to its high content in Irkutsk aluminum smelter air emissions. Fluoride pollution enhanced mobility of humic substances (Biryukova *et al.*, 1986; Pomazkina *et al.*, 2005). Soil index equaled 1.4 in DF soil, with 0.5 in unpolluted soil. An increase in the mobility of fluorides and in the content of exchangeable sodium in the soil DF lowered its buffer capacity towards sodium fluoride (B_{NaF}).

Table 2 Physical-chemical properties of gray forest soils (0-20 cm)

Soil	Sum of particles <0,01 mm, %	C_{org}	N_{tot}	pH_{water}	Ca^{2+}+ Mg^{2+}	Na^+	CEC	F_{tot}	F_{water}	DM	B_{NaF}*
		%			cmol(+)/100 g			mg/kg			
D	30.6	1.13	0.13	6.6	24.0	0.23	27.2	485	5	1	137
DF	31.9	1.47	0.14	7.0	22.0	0.60	26.9	820	57	7	32

In the last years of the monitoring (2009-2012) DF soil demonstrated decrease in water-soluble fluorides content (4 MPC), which is due to the migration into lower horizons. DM value decreased simultaneously (5.0 %), and the B_{NaF} value increased up to 68.

The impact of environmental factors on the carbon microbial transformation. Properties of DF soil and fluoride content, as well as hydrothermal parameters in individual years, affected microbial complex functioning (Table 3).

Table 3 The content of carbon of the microbial biomass (Cmic) and the rate of CO_2 emission in agroecosystems on unpolluted (D) and polluted (DF) gray forest soils in the years with different hydrothermic conditions

Soil	1997	2002	2004	2010	Long-term average (1997-2012)
The rate of the CO_2 emission, g/m^2 per day					
D	6.0±0.2	8.0±0.4	7.0±0.7	4.4±0.4	5.9±0.2
DF	8.2±0.3	7.8±0.3	6.9±0.6	4.3±0.3	6.4±0.3
$LSD_{0.95}$	0.62	0.51	0.88	0.70	0.40
Concentration of C mic, mg/100g					
D	29.9±3.0	18.4±2.5	20.5±3.0	24.2±3.0	25.1±1.4
DF	35.1±4.0	20.4±3.2	17.8±2.2	24.1±4.0	27.4±1.3
$LSD_{0.95}$	4.99	6.99	8.84	7.35	2.75

On DF soil the parameter of average multiannual rate of CO_2 emission was higher than on D soil (respectively 6.4 and 5.9 g/m^2 per day). In close to the norm 1997 it was higher (8.2 g/m^2 per day). In 2002 with low moisture availability, the rate of CO_2 emission on both soils was approximately the same and higher than in other years. In 2010 the parameters were lower, which is related to comparatively favorable geothermal conditions and with decrease of fluorides content in DF soil. Dependence of CO_2 emission rate on the content of water-soluble fluorides in the soil was high (r = 0.74). CO_2 emission is known to be used as an ecophysiological parameter characterizing response of soil microbe complex to the change in environmental factors (Anderson, 2003; Blagodatskaya *et al.*, 2016; Blagodatskaya *et al.*, 2013; Blagodatskii *et al.*, 2008; Semenov *et al.*, 2013).

Average monitoring content of carbon microbial biomass (C mic) in both soils, as well as its insignificant differences in individual years confirm that the parameters did not depend much on fluoride pollution (Table 3). On both soil types in favorable 1997 and 2010 they were slightly higher. Small differences in average multiannual C mic content, as well as low variability on different soils (19 and 22 %), demonstrate the same participation in the formation of active pool of newly formed carbon-containing substances (Pomazkina, 2015; Semenov *et al.*, 2011).

Statistical analysis demonstrated dependence of carbon transformation on soil pollution with fluorides and hydrothermal factors. The D soil demonstrated linear relation between CO_2 emission speed and air temperature (r = 0.51). Correlation proportion (η = 0.54) and determination ratio (η^2) prove that it depended on air temperature by 29 %. Relation with soil moisture content proved reverse and weak (r = -0.18), with low determination ratio (12 %). On DF soil linear relation between CO_2 emission speed and air temperature was lower (r = 0.45), than on D soil, and the correlation proportion index was low, as well as determination ratio (3-5 %). Dependence between CO_2 emission and the soil water content was unreliable.

On both soils there was no linear relation between C mic content and hydrothermal factors was absent. Weak impact was shown by correlation proportion and determination ratios. The analysis of relationships between the environmental factors and the C mic content allows us to assume that they mainly have nonlinear patterns, which are difficult to estimate under conditions of a field experiment.

Table 4 Soil carbon fluxes in the agroecosystems on the unpolluted (D) and polluted (DF) gray forest soils in the years with different hydrothermic conditions

Soil	1997	2002	2004	2010	Long-term average (1997-2012)
Mineralized carbon (M), mg C/ 100 g					
D	75.3	78.1	74.2	62.5	70.6±1.9
DF	105.2	85.8	76.8	62.1	83.0±3.0
Net-mineralized carbon (N-M), % of M					
D	60	76	72	61	65
DF	67	76	77	61	67
(Re)immobilized carbon (RI), % of M					
D	40	24	28	39	35
DF	33	24	23	39	33

Indifferent years of monitoring at the background of climatic changes soil microorganisms mainly responded to fluoride pollution with respiration enhancement. CO_2 emission speed depended more on air temperature than on soil moisture content. The calculations showed that monitoring average overall vegetation emission in agroecosystem on D soil amounted to 175, and on polluted DF soil - 193 g C/m^2 year. Taking into account the parameters over non-frost period the parameters attained respectively 230 and 254 g C/m^2 year (Pomazkina, 2015). Representative data of long-term monitoring in agroecosystems on gray forest soil of Baikal region forest-steppe prove that technogenic pollution of soils with fluorides may be considered negative anthropogenic factor affecting CO_2 introduction into the atmosphere and carbon losses depending on destruction of organic matter, particularly from fluoride-polluted soil.

As far as C mic content is concerned, indifferent years of monitoring the differences revealed during the vegetation apparently did not go beyond the limits characteristic of the microbe soil complex functioning, which ensures adaptation to environmental factors change in concrete soil-climatic conditions. The concept of universal character of oscillating properties in the development of microbial community with the change of environmental factors is widely used in biodiagnostics, succession control, as well as in the development of ecological indices of soil quality and health (Semenov *et al*., 2011; Sokolov *et al*., 2011 *et al*.). It is also noted that evaluation of microbial community functioning depending both on soil properties and environmental factors, would benefit from using a complex of parameters including integral ones (Anderson, 2003; Pomazkina, 2004, 2015 *et al*.). The role of microbial complex in carbon transformation in soil characterizes relative C mic complex (C mic/C org, %), or its contribution to renewal and maintenance of active carbon pool. Average monitoring parameters in agroecosystems on D soil were higher than on polluted DF soil (3.1 and 1.8 % respectively). No less significant differences were in some years. In norm-close 1997 the parameters were higher (3.9 %) than in anomalous 2002 and 2004 (2.3 and 2.2 % respectively), their sharpest decrease was observed on DF soil (1.4 and 1.3 %). Low relative C mic content and increase in C-CO_2 emission characterize possible degradation of organic matter in fluoride-polluted soil. The results agree with those published. The parameters C mic/C org and C-CO_2 emissions are used not only for diagnostics of soil fertility, but for evaluation of agroecosystem status (Anderson, 2003; Insam *et al*., 1988; Semenov *et al*., 2011 *et al*.).

Dependence of the activity of microbial complex functioning on environmental factors is demonstrated by the parameters of carbon mineralized (M) over the vegetation (Table 4). Despite differences in individual years, M parameters was higher on DF soil than on D soil, and on average over the monitoring period it amounted to 83.0 and 70.6 mg C/100 g respectively. In close to the norm1997 M value increased, with higher increment on DF than on D soil (105.2 and 75.3 mg C/ 100 g respectively). In unfavorable years the parameter was lower, as well as pollution-dependent differences. The role of microbial biomass in the formation of carbon available for mineralization proved the dependence between C mic and M value (r = 0.49 and 0.58 respectively on D and DF soils). Quantitative valuations of carbon mineralized over vegetation do not contradict those known for gray forest arable soils.

The impact of mineralization on carbon intra-soil cycle was identified in the experiments. On each of the soils most of carbon mineralized over the vegetation was subjected to C-CO_2 emission. Average multiannual parameter of carbon N-M on DF soil amounted to 67 % of M, as well as in favorable 1997. In anomalous years, for example, in droughty 2002, on DF soil M value was higher (85.8 mg C/ 100 g), and the share of N-M carbon equaled 76 % of M. In favorable 1997 and 2010 carbon (re)immobilization increased (33 and 39 % of M respectively), while pollution-related differences were smaller. On both soils 2010 similar RI carbon parameters are apparently accounted for by the decrease of fluorides content on DF soil.

Optimal functioning of any system (according to systemic analysis (Odum, 1986)) is possible with the consumption of no less than 50 % of the substance entering the system. As noted above, formation of (re)immobilized carbon is partially linked with secondary inclusion of M carbon into C mic following re-synthesis or recirculation (% of return at the exit) inducing maintenance and partial renewal of active carbon pool in the soil. Use of systemic analysis for over view of the results facilitated identification of negative fluorides pollution impact on formation of the regimes of agroecosystems functioning at the background of changing climatic factors (Fig. 2).

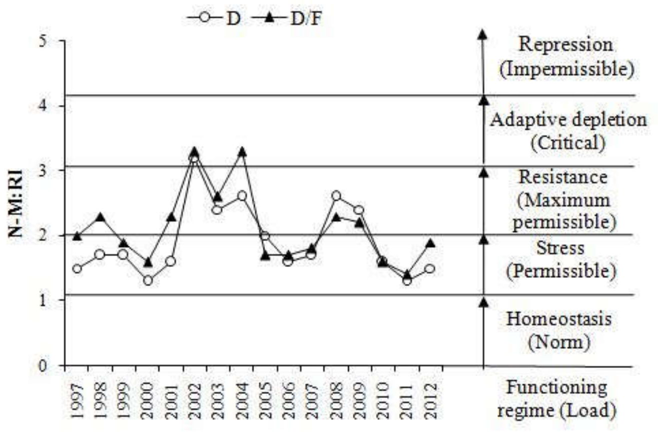

Fig 2 Changes in the regimes of functioning of the agroecosystem under spring wheat on unpolluted (D) and fluoride-polluted (DF) soils

Thus, in close to the «norm» of 1997 on unpolluted soil D, the agroecosystem functioned under stress conditions (permissible load), which provided a relatively high recirculation of carbon (40 % of M), which reduced the ratio of N-M:RI. As previously shown (Pomazkina, 2011; Pomazkina *et al*., 2013), in agroecosystems with crops such a regime was conditioned by the load, typical of agriculture in the region. In the same year on polluted DF soil the rewash formed resistance regime (maximum permissible load), which depended on high carbon mineralization accompanied by the increase of C-CO_2 emission (67 % of M). On DF soil in anomalous 2002 and 2004 the rewash formed adaptive depletion regime (critical load) conditioned by reduction in RI carbon, whereas N-M flow amounted to 76 % of M. Such regime related to enhancement of C-CO_2 emission in droughty 2002 was registered on unpolluted soil. Adaptive depletion regime on DF soil both in droughty 2002 and in the most humid 2004 depended on reduction of RI carbon (23 % of M). In the following years close to climatic norm (2005-2007), as well as in 2010-2012, the last ones covered by the monitoring, (re)immobilization increase induced stress regime (permissible load). The increase of the load due to hydrothermal conditions in 2008 and 2009 on both soils contributed to the formation of resistance regime. Therefore, over view of the results of 16-yearlong monitoring on the basis of systemic analysis and the approach developed for integral evaluation of agroecosystem status and functioning, proved to be instrumental in identification of the ecological load, which depended simultaneously on climatic conditions and on the impact of soil pollution with fluorides at their background.

CONCLUSIONS

In the only Siberian long-term ecological monitoring in field experiments on gray forest soil at the background of modern climatic changes experiments revealed negative impact of soil technogenic pollution with aluminum production fluorides on carbon microbe transformation and related regimes of agroecosystem functioning (soil-microorganisms-plants-atmosphere).

*For the first time the monitoring (1997-2012) showed annual veg*etation deviations from «climatic norm» of hydrothermal parameters related to the trend of temperature increase, unlike precipitation fluctuations. *Anomalous and norm-close years were identified. Differences in the functioning of soil microbe complex were experimentally shown to depend both on hydrothermal factors, and on pollution of gray forest soil with fluorides. Microorganisms response to pollution showed in the enhancement of respiration, particularly in anomalous years, with* CO_2 emission speed depending on air temperature increase rather than soil moisture content.

Based on the representative data of the monitoring, for the first time for Baikal Siberia forest-steppe there was calculated average multiannual vegetation C-CO_2 emission, whose parameters in agroecosystems on technogenic polluted soil are higher than on unpolluted. Throughout non-frost period the emission reached respectively *230 and 254 g C/m^2 year. Average over 16 years* monitoring data showed that pollution of arable soils with fluorides may be regarded as a negative anthropogenic impact which contributes to the increase of CO_2 emission to the atmosphere and decrease of carbon resource in the soil.

Over view of the results of long-term monitoring based on the use of comparative and systemic analysis showed that ecophysiological parameters characterizing the role of soil microbe complex in carbon transformation are efficient for integral assessment of agroecosystem functioning and status in changing environmental conditions. For example, average multiannual value of carbon mineralized over vegetation (M) on polluted DF soil was higher than on unpolluted soil. C-CO_2 emission forming net-mineralized (N-M) carbon flow, on DF soil amounted to 67 % of M, whereas the flow of (re)immobilized carbon (RI) decreased to 33 %. The parameter N-M:RI characterizing functioning regime (adaptive depletion) and the load (critical) in agroecosystem on DF soil demonstrates destruction processes taking place at the background of unfavorable hydrothermal factors in agroecosystems on fluoride-polluted soil. The necessity to enhance processes of carbon (re)immobilization forming active pool of newly formed carbon-containing substances, which are amenable to mineralization is of specific interest, as it contributes to agroecosystem resistance, particularly under negative environmental impact. Presumably, soil microbe activity related to the increase of (re)immobilized carbon forms not only agroecosystem resistance, but their biospheric functions.

Synthesis of the results of the study results in a long-term monitoring with the use of systemic analysis and integral evaluation gives a possibility to assess differences in functioning, state and status of agroecosystem resistance, which depended both on the change in climatic conditions, and on the impact of soil pollution with fluorides at their background. On ecosystem level integral evaluation of environmental factors impact was conducted for the first time and may be used to forecast state and scenarios of agroecosystem development.

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