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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

The Impact of a Large Industrial City on the Soil Respiration in Forest Ecosystems

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Abstract—The rate of soil respiration was measured in situ under native pine stands in a large industrial city (Yekaterinburg, Russia) and beyond it. The compared sites differed significantly in the two factors affecting soil respiration, i.e., in the degree of urbanization (including air pollution, changes in the microclimate, fragmentation of the biotopes, the appearance of introduced species, etc.) and in the character of recreation loads (primarily, trampling loads). The difference between soil respiration rates in the city and in the suburbs was significant; it reached its maximum in the summer, when the soil respiration in the city was 1.9–3.5 times lower than that in the suburbs. However, this difference was virtually absent in the spring and fall seasons. The impact of recreation loads on the soil respiration was relatively low; moreover, it could have both positive and negative signs, i.e., lead to the increase or decrease in the soil respirarion rate. The particular mechanisms explaining the influence of the considered factors on the rate of the CO_2 emission from the soils are discussed.

Keywords: carbon dioxide emission, soil respiration, urbanization, recreation, pine forests, Middle Urals

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INTRODUCTION

At present, urbanization is a global process, though, according to some forecasts, the growth of cities on the planet may stop in 2050 [46]. The contribution of the cities to the global anthropogenic CO_2 emission reaches 97% [47], which specifies their importance in the planetary carbon cycle. To improve the accuracy of such estimates, a more detailed analysis of the influence of various aspects of urbanization on the processes of the carbon cycle should be performed. Soil respiration is one of the key components of the carbon cycle. It has a complex nature and reflects the intensities of both productive (respiration of autotrophs) and destructive (respiration of heterotrophs) processes [34, 36].

There are many works devoted to the CO_2 emission from urban territories. Most of them are based on the analysis of the fluxes of carbon dioxide with the use of the Eddy covariance method [24, 29, 30, 50]. Other works are based on the analysis of respiration of samples of urban soils under laboratory conditions [7, 37, 38]. The in situ measurements of soil respiration in the cities have mainly been performed for open biotopes (lawns) of artificial origin, mostly within the limits of the cities [2, 22, 45, 52, 53], though they are sometimes compared with respiration from the natural analogs of these ecosystems [32]. Data on the rates of soil respiration under natural forests in the cities are very scarce [24, 29].

One of the major factors related to urbanization is the environmental pollution with heavy metals [42]. The studies of the impact of this factor on soil respiration have mainly been performed in the ex situ conditions of laboratory experiments in the course of determination of the microbial biomass by the method of substrate-induced respiration [1, 26, 33, 41, 42, 51]. Studies of the impact of soil contamination with heavy metals on the rate of soil respiration measured in situ are not numerous and are relatively ambiguous [8, 17, 33, 43, 44].

The impact of recreation loads—a factor that usually accompanies urbanization—on soil respiration is also insufficiently studied [21, 37]. The major soil disturbances under the impact of recreation loads are related to the increase in the density of the mineral horizon and to the mechanical destruction of the litter horizon [15].

To assess the impact of urbanization on soil respiration in natural forest ecosystems growing in the cities, we have to compare the rates of soil respiration in these ecosystems and in their analogs beyond the impact zone of the cities. In this case, the notion of urbanization implies multiple impacts on the biota of the urban environment, except for recreation loads. These impacts include the chemical, heat, light, and noise pollution of the urban environment; the changes in the microclimatic conditions; the fragmentation of the biotopes; the destruction of natural landscapes;

the construction of artificial landscapes; the invasion of alien species; etc. In the large industrial cities, the anthropogenic loads in the environment are related to the urbanization proper and to recreation loads. To distinguish between their impacts, we have to compare suburban and urban biotopes with contrastingly different recreation loads. Thus, the simplest experimental design should include two sites subjected to strong urbanization loads in the city and two analogous sites in the suburban area (beyond the impact zone of the city). In each of these pairs, one of the sites should be subjected to considerably stronger recreation loads than the other site. In this case, we can judge the influence of both urbanization and recreation loads on the soil respiration.

The aim of our study was to analyze changes in the rates of the CO_2 emission from the soil surface under native pine forests in the impact zone of a large industrial center (in Yekaterinburg) and beyond it. The impacts of the urbanization factor and recreation loads on the soil respiration were separately assessed.

OBJECTS AND METHODS

Field studies were performed during the growing seasons of 2010–2011 on four sites with different combinations of the two studied factors: urbanization (U) and recreation (R). Hereinafter, the presence of a given factor is designated by the + sign; its absence is designated by the – sign. Two of the studied sites are located in Yekaterinburg: in the arboretum of the Botanical Garden of the Ural Division of the Russian Academy of Sciences (which is closed for visits by the local population, so that significant recreation loads on this site are absent) (U+ R–) and in the nearby Yugo-Zapadnyi forest park subjected to considerable recreation loads (U+ R+). Two sites beyond the impact zone of the city are found 16 km to the southwest of Yekaterinburg. One of them (in the area of Lake Glukhoe) is rarely visited by people (U– R–), whereas the other one (in the area of Lake Chusovkskoe) is subjected to strong recreation loads (U– R+).

Yekaterinburg is an industrial megalopolis in the Middle Urals; its area is about 50 000 ha, and its population is about 1.4 million people. This is one of the most strongly polluted cities in Russia [12]. In 2012, industrial emissions of Yekaterinburg reached 215 000 t (including sulfur, carbon, and nitrogen compounds; mineral dust; and heavy metals). The most significant contribution to the atmospheric pollution in Yekaterinburg (up to 85%) belongs to motor vehicles [5].

Forest parks occupy almost a quarter of Yekaterinburg (12 300 ha) [5]; most of them are of natural origin; i.e., they represent the remains of native forests in the city. Most of the forests around the city are also of natural origin. Thus, we could select analogous natural objects to compare soil respiration under the impact of urbanization and recreation loads on the soil biota.

The main characteristics of the studied ecotopes in the city and in its suburbs are comparable (Table 1). Mature pine stands of moderately high stand density were analyzed. The average age of the trees was about 120–140 years [20]. The pine stands of the city contain the admixture of adventive species (American maple, apple trees, lilac, bird cherry, shadbush, and cotoneaster) in the well-developed understory (these species are usually planted in the city). Synanthropic nitrophile species (*Glechoma hederacea* and *Urtica dioica*) predominate in the ground cover in the city [6]. This attests to the increased nitrogen content in the soil; analytical determinations prove this fact (Table 1).

The development of the understory leads to considerable shadowing of the soil surface in the city; the total canopy density reaches 75–85%; in the pine stands of the suburbs, it is usually about 20%. Under the shadow of the trees, the density of the layer of herbs and small shrubs in the city is lower than that in the suburbs. The soils of the city are also characterized by a somewhat higher water content. On the site subjected to strong recreation loads, the network of roads and paths is well developed; the area subjected to strong trampling loads reaches 10–40% of the total area [6].

The soils of the studied sites are represented by typical and podzolized brown forest soils (burozems). They are characterized by a slightly acid reaction. The contents of heavy metals in the soils of the sites studied in the city and beyond it are approximately the same (Table 1). This contradicts the official information about the high degree of soil contamination with heavy metals in Yekaterinburg [5]. However, the official data reflect the state of the soils in the central parts of the city under the lawns, whereas our data concern the soils of the peripheral part of Yekaterinburg under natural forests that protect the soil from the direct input of the pollutants from the atmosphere. The main differences of the soils in the city from the soils in the suburban area consist in higher pH values (by 0.2–0.5 pH units), higher concentrations of nitrates and available nitrogen compounds (by 2–5 times), and smaller thickness of the litter horizons (by 1.5–1.7 times) [3].

The measurements of soil respiration were performed by the closed dynamic chamber method [36] with the use of an SR1LP (Qubit Systems, Canada) soil respiration package. The chamber was inserted into the soil (to the depth of 1–2 cm) for 2–3 min. After insertion, air circulation took place in the closed systems consisting of the chamber itself (10 cm in diameter), the flow meter, and the infrared gas analyzer connected to a computer. The flow rate was 450–500 mL/min. The concentration of carbon dioxide released from the soil into this closed system usually increases linearly. The rate of the soil respiration was computed from the slope of the curve showing the accumulation of CO_2 in the system with consideration for its volume and the area covered by the chamber. For such calculations, a segment of the linear curve

Table 1. Characterization of the studied plots

Parameter	U–		U+	
	R–	R+	R–	R+
Soil				
Bulk density of the A1 horizon, g/cm^3*	0.84	0.78	0.84	0.84
Thickness of the litter, cm*	1.4	1.4	0.8	0.9
pH_{H_2O}**				
A0 horizon	5.3	5.3	5.7	5.7
A1 horizon	5.5	5.5	5.6	5.7
Base saturation, %**				
A0 horizon	31	22	51	56
A1 horizon	41	45	45	57
Contents, mg/100 g soil**				
P_2O_5				
A0 horizon	37.5	17.5	20	43.45
A1 horizon	10	7.3	2.5	6.9
Hydrolyzable N compounds				
A0 horizon	22.4	12.6	30.7	43.6
A1 horizon	6.1	3.7	5.6	6.9
Storage in the layer of 0–50 cm, mg/m^2*				
Cu	7.5	9.2	11.4	6.5
Pb	4.2	5.4	5.1	5.0
Cd	0.1	0.2	0.1	0.1
Zn	10.3	11.8	9.5	8.2
Vegetation				
Projective cover of the ground vegetation layer, %***	79.2	65.8	40.0	30.8
Phytomass of the ground vegetation layer, g/m^2***	90.4	40.4	6.8	19.2
Portion of synanthropic species in the projective cover, %***	0	21.1	88.2	88.3
Timber storage, m^3/ha****	523.9	447.8	343.5	464.7

* Data of S.Yu. Kaigorodova. ** Data from [3]. *** Data from [6] **** Data from [20].

with the highest determination coefficient (>0.97) obtained at least 30 s after the beginning of the measurements was used.

The soil temperature was measured with the help of a soil temperature probe (included in the package) with the accuracy of 0.1°C. The volumetric soil water content was measured by a soil moisture sensor (Delta-T Devices, United Kingdom) with the accuracy of 0.1%. The measurements of the soil moisture and temperature were performed at the point of the gas flux measurements at the depth of 5 cm.

On each of the sites, three sample plots 25 × 25 m in size were investigated (overall, 12 sample plots). The measurements of soil respiration were performed on these plots at ten randomly selected points spaced at least 5 m apart from one another. The measurements were not performed close to the trunks (>1 m) or immediately under the paths. There were seven rounds of measurements: three rounds in 2010 (at the beginning of June, in the middle of August, and at the end of September) and four rounds in 2011 (in the middle of May, at the end of July, in the middle of October, and at the end of September). Each time, the measurements were performed at different points. Data on weather conditions during the period of measurements are presented in Table 2.

The measurements of soil respiration were performed in the middle of the day (10 a.m. to 4 p.m. local time). To minimize possible shifts of the respiration activity because of its daily dynamics, the plots were vis-

Table 2. Characterization of weather conditions in the periods of measurements

Parameter	Dates of measurements						
	2010			2011			
	June 2–3	Aug. 18–20	Sept. 28	May 18–20	June 26	Oct. 11–12	Oct. 20–21
Weather conditions on days of measurements							
Soil temperature, °C*	11.5 ± 0.2	12.6 ± 0.3	8.6 ± 0.1	8.0 ± 0.1	19.4 ± 0.3	10.4 ± 0.1	6.2 ± 0.0
Soil moisture, %*	29.4 ± 0.8	8.4 ± 1.1	11.9 ± 0.7	19.2 ± 0.5	27.5 ± 1.1	20.7 ± 1.1	18.8 ± 0.9
Air temperature, °C**	16.3	14.0	5.6	13.7	24.8	13.3	4.5
Air moisture, %**	88.6	69.2	75.5	52.5	61.1	63.1	74.9
Weather conditions 10 days before the measurements**							
Mean daily air temperature, °C	13.5	21.1	13.4	9.6	19.6	7.7	8.7
Mean daily air moisture, %	65.5	59.1	63.9	45.9	78.8	87.1	70.4
Precipitation, mm	39.4	8.7	10.8	0	23.5	53.6	0.8

* Mean ± error of the mean; calculations are made for separate measurements ($n = 120$). **According to the Weather Archive website (rp5.ru).

ited at different times (during the given round of measurements). As the measurements were performed on many plots, a narrower time interval for them (e.g., over a period of 1–3 h) would prolong the duration of a given round up to 4–7 days, and this could lead to an even greater error because of the weekly and seasonal dynamics of the soil respiration, since these components of respiration variability are more significant than the daily dynamics [11]. A three-way ANOVA was applied for the statistical treatment of the data, and Tukey's range test was used for multiple comparisons.

RESULTS

The rate of soil respiration ranged from 103 to 1777 mg CO_2/m^2 per h on the suburban plots and from 103 to 1076 mg CO_2/m^2 per h on the urban plots (Fig. 1). The seasonal dynamics of soil respiration were clearly pronounced on all the plots; the maximum rates were observed in the summer. At the end of the growing season, soil respiration on the suburban and urban plots was 1.8–3.3 and 0.9–2.5 times lower than that in the middle of the summer, respectively. The most pronounced difference between respiration intensities on the urban and suburban plots was observed in the summer: soil respiration in the city was 1.9–3.5 times lower than that in its suburbs (at $p < 0.05$). In the spring and fall months, the difference was statistically insignificant (p = 0.1–1.0); in the most contrasting case, soil respiration on the suburban plots was 1.6 times higher than that on the urban plots. In other words, at low temperatures, soil respiration on the urban and suburban plots was approximately the same. The interaction between the effects of the round of measurements and the urbanization ("round × urbanization") was significant in both years of our study (Table 4).

The results of a three-way ANOVA performed for both years showed significant differences between respiration intensities in different rounds and on the plots with different urbanization and recreation loads. The influence of recreation loads on soil respiration was ambiguous. In 2010, soil respiration on the plots under recreation loads was 1.2 times lower than that on the plots without recreation loads. In 2011, the average rate of soil respiration on the plots subjected to recreation loads was 1.1 times higher than that on the plots without recreation loads (Table 3). The "urbanization × recreation" interaction was significant in 2010, and the "round × recreation" interaction was significant in 2011. Such an inconstancy indirectly attests to the weak influence of the recreation factor.

Table 3. Emission of carbon dioxide (mg CO_2/m^2 per h) from the urban and suburban plots (mean ± standard error; the calculations are made for sample plots, $n = 3$)

Year and date of the beginning of measurement	U–		U+	
	R–	R+	R–	R+
2010				
June 2	1091 ± 9	909 ± 76	492 ± 13	478 ± 97
Aug. 18	887 ± 15	730 ± 24	231 ± 1	232 ± 6
Sept. 28	596 ± 18	489 ± 14	571 ± 19	482 ± 7
2011				
May 18	511 ± 41	277 ± 22	244 ± 9	277 ± 44
June 26	1480 ± 9	1678 ± 11	750 ± 7	863 ± 18
Oct. 11	990 ± 47	1158 ± 34	677 ± 19	696 ± 42
Oct. 20	493 ± 36	514 ± 10	305 ± 12	399 ± 14

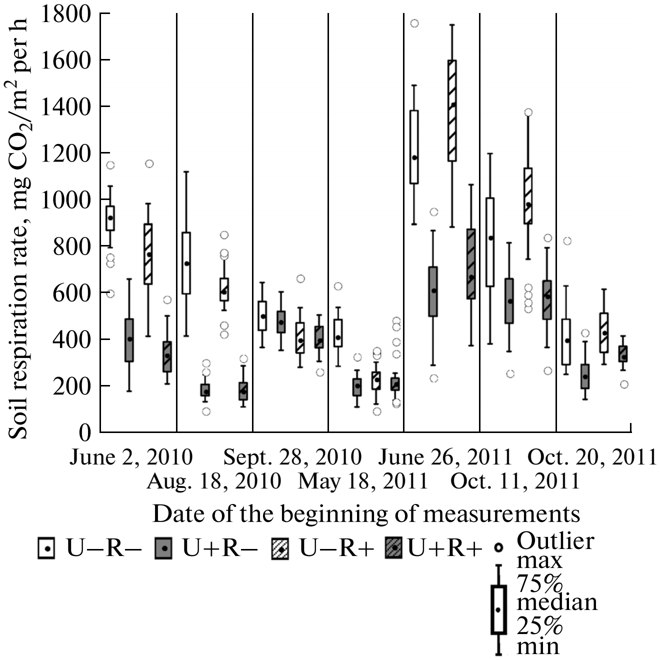

Fig. 1. Soil respiration on the studied plots in different rounds of measurements. The results of measurements at particular points are shown. The duration of measurement periods is given in Table 2. Designations of the experimental variants are explained in the "OBJECTS AND METHODS" section. Outliers are the values beyond the median ± interquartile range interval; min/max is the nonoutlier range.

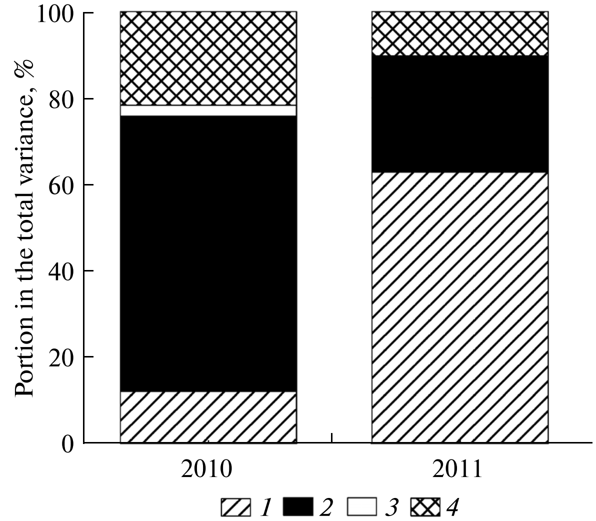

Fig. 2. Component of the variance (%) of the soil respiration. Variances specified by the differences between (*1*) rounds of measurements, (*2*) urbanization loads, and (*3*) recreation loads; (*4*) residual variance. The calculations are made on the basis of the results averaged for sample plots.

The coefficient of variation of the soil respiration ranged within 13–31% (22.5% on average) as calculated for individual measurements. No regular changes in this coefficient on different plots and during different rounds of the measurements were noted. The absolute values of variation (amplitude) of the CO_2 emission in summer reached 1000 mg CO_2/m^2 per h on the suburban plots and 800 mg CO_2/m^2 per h on the urban plots (Fig. 1). In the spring and fall (upon low soil temperatures), the amplitude of variation of the CO_2 emission was 1.5–3.5 times smaller. The values obtained on different plots at least partially overlapped during all the rounds of the measurements.

The relationships between the particular components of the total variance in 2010 and 2011 were different. Thus, the difference between the rounds contributed to about 10% of the total variance in 2010 and to more than 60% in 2011 (Fig. 2). The urbanization factor explained 65% of the total variance in 2010 and only 25% in 2011. The effect of the recreation factor was only seen in 2010 and contributed to about 2% of the total variance.

DISCUSSION

The rates of soil respiration on the suburban plots in the summer months (800–1400 mg CO_2/m^2 per h) are close to the values reported for soil respiration under forests of the temperate zone (in mg CO_2/m^2 per h): 300–1400 [4], 440–1060 [8], 1000–1500 [13], 625–1100 [17], and 690–1800 [33]. The spatial variability of soil respiration is also close to that typical of natural soils [36]; the coefficients of variation calculated by us are close to those reported for the middle taiga zone [9]. The seasonal pattern of changes in the rate of the CO_2 emission with a maximum in the summer months is similar to the pattern described for the southern taiga soils [12].

As the measurements on particular days lasted from 10 a.m. to 4 p.m., some variability in the rates of soil respiration could reflect its daily dynamics controlled by the soil temperature and by the time lag between photosynthesis and the input of its products to the roots [11, 35, 36]. To level this variability, it is recommended to perform respiration measurements during relatively short time intervals in the morning (9 to 12 a.m. [12, 27] or 10 to 11 a.m. [11]). The rate of soil respiration in these hours is close to the mean daily rate. However, under the forest canopy, the daily dynamics of soil respiration are less pronounced than those under open biotopes [25]. This is explained by the narrower range of soil temperature fluctuations under the forest canopy [36] and by the lower temperature sensitivity of soil respiration [10]. Hence, an enlarged interval of respiration measurements under the forests is not critical (in comparison with that for the open (not shadowed) biotopes. At the same time, we should take into account the fact that the obtained coefficient of variation of soil respiration on the studied plots reflects not only the spatial variation but also

Table 4. The results of a three-way ANOVA to study the differences in soil respiration between different rounds of measurements and the levels of urbanization and recreation loads

Source of variance	2010			2011		
	df_1	F	p	df_1	F	p
Round	2	42.6	<0.0001	3	733.8	<0.0001
Urbanization	1	299.1	<0.0001	1	627.3	<0.0001
Recreation	1	17.3	0.0004	1	14.0	0.0007
Round × urbanization	2	69.3	<0.0001	3	100.7	<0.0001
Round × recreation	2	0.2	0.8478	3	14.8	<0.0001
Urbanization × recreation	1	6.8	0.0155	1	0.9	0.3554
Round × urbanization × recreation	2	1.2	0.3195	3	11.4	<0.0001

F is Fisher's test, p is the significance level, and df_1 is the number of degrees of freedom for the given factor. The calculations are made for sample plots.

the temporal (daily dynamics) variation in the intensity of this process.

In general, however, the daily variability in the rate of soil respiration (within the studied time interval) was relatively small; the average difference in soil temperatures for all the plots within the given round of measurements was 17 ± 3%. This is a relatively small difference, and it could not significantly affect the intensity of soil respiration. The maximum absolute difference in soil temperatures between the plots in the given round was recorded in August 2010 for the two suburban plots; it reached 3°C. The rates of soil respiration on these plots differed by 20%. This difference is much smaller than the average difference between the suburban and urban plots—more than 200%.

The results obtained by us attest to a clearly pronounced negative influence of the urbanization factor on soil respiration. This conclusion is in agreement with the results obtained by Chen et al. [24] on soil respiration in forest ecosystems, but contradicts the materials on soil respiration of city lawns and open native suburban biotopes [32].

Different environmental factors that specify multiple action of urbanization on the ecosystems may exert differently directed (though, mainly adverse) impacts on the autotrophic and heterotrophic components of soil respiration. On one hand, atmospheric pollution, increased density of the soils, and unbalanced state of major nutrients (nitrogen, phosphorus, and potassium) suppress plant growth [16], hamper root colonization by mycorrhizal fungi [28], and decrease the diversity of mycorrhizal fungi [40], which should lead to a decrease in root respiration. On the other hand, the heat pollution in the cities extends the period with biologically active soil temperatures (>10°C), during which active growth of the roots of trees and shrubs in the temperate zone is observed [28]. The increased CO_2 concentration in the air of the cities [47] improves the conditions of photosynthesis. These factors may exert favorable influence on the intensity of root respiration. The microbial activity of soils in urban ecosystems is usually suppressed, which is usually related to the adverse impact of the increased concentrations of heavy metals [16, 41, 42, 47, 51] on the biomass and diversity of soil microorganisms.

In addition, urbanization may affect the physical mechanisms of the emission of carbon dioxide from the soil surface in the city via decreasing wind velocity [16] and increasing CO_2 concentration in the atmosphere [47]. The higher bulk density of the mineral soil horizons in the cities may slow down the CO_2 diffusion from the soil into the atmosphere.

In our study, the concentrations of heavy metals on all the plots were very similar (Table 1). Thus, we can suppose that the negative impact of urbanization on soil respiration processes under the forest canopy is not directly related to the soil contamination. It is probable that an indirect impact of changes in the vegetation cover is more important. The appearance of adventive species in the understory increased the shadowing of the lower vegetation stories and weakened the development of herbs in the ground layer. The projective cover and the aboveground phytomass of the ground vegetation layer in the city are 2–10 times lower than those in the analogous ecosystems in the suburbs [6]. Though we have not directly determined the pools of the underground phytomass on the studied plots, this fact allows us to assume that the number of roots contributing to the soil respiration in the urban forests is much lower than that in the suburban forests. According to different estimates, the contribution of the root respiration to the total soil respiration may vary from 10 to 90% (on the average, about 50%) [30, 31, 48]. It is probable that the difference in the CO_2 efflux from the soils of the urban and suburban plots in the middle of the growing seasons is related to the lower contribution of root respiration to the total soil respiration in the urban forests. The productivity of the lower (ground vegetation) layer plays the major role in this difference, because the biomass of the trees is approximately the same on all the plots (Table 1).

The changes in the soil respiration observed during different rounds can be attributed to seasonal changes in the soil moisture and temperature. In the cold periods (September 28, 2010; May 15, 2011; and October 20, 2011), when the soil temperature dropped below +8°C, the difference between the rates of respiration on the urban and suburban plots virtually disappeared. Taking into account a much higher temperature sensitivity of the roots in comparison with temperature sensitivity of the microorganisms [10, 23], this fact can be considered indirect evidence in favor of our hypothesis of the decisive role of root respiration in the differences between the rates of soil respiration on the urban and suburban plots. A decrease in the rate of root respiration in the fall can be related not only to the drop in the soil temperature but also to the seasonal decrease in the intensity of photosynthesis in the period of transition of the plants to the dormant state, because the intensity of photosynthesis is also an important factor affecting soil respiration [14, 35].

Summing up this discussion, we argue that the lower intensity of soil respiration in the urban pine stands in comparison with their suburban (beyond the impact zone of the city) analogs can be explained as follows. Under the impact of urbanization, tree and shrub species typical of the understory of pine stands in the studied region were suppressed and replaced by adventive (introduced) species [6]. The active development of the latter resulted in the strong shadowing of the lower (ground vegetation) layer. The phytomass of herbs and low shrubs in the urban pine stands decreased considerably in comparison with that in the undisturbed native pine stands. The lowering of the aboveground phytomass of herbs and shrubs was also accompanied by the decrease in the number of actively respiring roots, which led to the significant difference between the intensities of soil respiration on the urban and suburban plots.

The impact of the recreation factor on the soil is mainly related to the trampling loads [15] that increase the bulk density of the mineral soil horizons. In turn, this may enhance anaerobic processes, reduce the organic matter content, and decrease respiration intensity. Some authors argue that recreation loads may increase the CO_2 emission from the soil surface [21]; in other works, the negative impact of recreation loads on the soil respiration is shown [37]. In our study, the impact of recreation loads on the soil respiration was positive in the first year and negative in the second year of measurements. However, in both cases, its influence was not strong. It should be stressed, however, that we measured soil respiration beyond the network of roads and paths created by the recreation loads. Thus, the influence of this factor on the soil respiration could be underestimated.

CONCLUSIONS

The analysis of the intensity of soil respiration under pine forests in Yekaterinburg and in its suburbs showed the negative influence of urbanization on the CO_2 emission from the soil surface. In comparison with the urbanization factor proper, the influence of the recreation factor on the soil respiration was relatively small and differently directed in different periods. The influence of the urbanization factor was significant. The rate of the CO_2 emission in the middle of the growing season from the soils of pine stands in the city was a factor of two lower than that in the suburban pine stands. The suppressive effect of urbanization on the rate of soil respiration has an indirect character: it is related to changes in the species composition of the pine stands with the suppression of the herbaceous cover rather than to the direct impact of atmospheric pollution.

Thus, the urban environment exerts a significant negative impact on the intensity of the CO_2 emission from the soils of pine stands. Taking into account the global sprawl of urbanization processes in the modern world and the significant role of anthropogenic emission of carbon dioxide in the carbon budget of the cities, our finding about the decreased soil respiration under urban forests can be interpreted as a specific compensatory mechanism preventing the excessive accumulation of this greenhouse gas in the atmosphere of the cities. In turn, this conclusion implies the necessity of further examination of the influence of urbanization processes on the global carbon cycle.

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