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COMPARATIVE ANALYSIS OF PRINCIPAL FACTORS OF SPATIAL-TEMPORAL VARIABILITY OF $C0_2$ EMISSION FROM MOSCOW URBAN SOILS WITH VARIOUS LEVELS OF ANTHROPOGENIC IMPACT[1]

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Abstract: this paper presents the principal results of comparative analysis ofprincipalfactors of spatial-temporal variability ofCO-, emission from urban soils with various levels of anthropogenic impact that are typical for Moscow megalopolis ecosystems. The main set of objects includes natural sod-podzolic and pit-podzolic soils of RTSA U Forest Experimental Station, and urban constructed soils at the different functional zones of the city.

Key words: global changes, urban ecosystems, forest ecosystems, monitoring, CO-, emission, carbon stocks, urban soils, spatial variability, temporal dynamics, basal respiration, ecological models.

Terrestrial ecosystems are a major player in the global carbon cycle acting as carbon stocks and carbon sources (Ouimet, 2007). On the one hand, soil organic carbon (SOC) is the largest carbon stock in terrestrial ecosystems (Janzen, 2004). On the other hand, soil $C0_2$ emission is a predominant terrestrial carbon outflow, including autotrophic respiration of plant roots and heterotrophic microbial respiration (Blagodatsky et al., 1994; Kudeyarov et al., 1999; Chapin et al., 2006). The capacity for carbon sequestration is widely accepted as a principal soil function (MEA, 2005; Blum, 2005; Kudeyarov et al., 2007/Soil respiration is assumed as an important carbon source, included in the majority studies, assessing carbon budget (Nilsson et al., 2000; IPCC, 2001; Parton, 2001).

SOC stocks and especially $C0_2$ emission demonstrates a very high spatial and temporal variability, which may have a strong influence on regional land-use change

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strategy and climate change, thus quite a few studies focus on this problem (Ananyeva et al., 2008; Stoorvogel et al., 2009; Gruniberg, 2010).

General literature indicates various factors to influence carbon stocks' and fluxes' variability in a region: soil type (Dobrovolsky, 2004), land-use (Lai, 2002; Zhou, 2007 et al) and the level of urbanization (Pouyat et al., 2006). Whereas quite a few studies focus on analyzing and mapping $C0_2$ emissions for natural and agricultural soils (Guo, 2002; Zhou et al., 2007; Kurganova et al., 2009), soil $C0_2$ outflow in urban conditions turns to be beyond the scope for vast majority of research. However, considering that urbanization is one of the predominant recent land-use change pathways (Saier, 2007; Picket et al., 2011) and urban lands can occupy as much as 10% of a region's territory, their contribution to the regional $C0_2$ emission cannot be neglected.

The urban environment brings about anumber of specific features that requires certain approaches in its analysis: high short-distance variability, peculiarities of settlement history, functional zoning, and soil sealing. Urbanization has a significant and versatile impact on $C0_2$ emission. On the one hand, new-formed soils and turf grasses have high potential capacity for carbon sequestration, caused by high cation exchange capacity and humic/ fulvic acid ratio of topsoil, as rule introduced from the outside (Greg, 2003; Prokofieva and Stroganova, 2004; Smagin, 2005). On the other hand higher average temperatures, caused by "heat island effect”, usage of mineral fertilizers, unstable water conditions non-typical for introduced substrate as well as contamination with heavy metals and oil intensifies SOC decomposition and thus increases soil respiration (Ananyeva et al., 2003; Kaye, 2005; Vasenev, 2011).

One of the main factors, influencing soil $C0_2$ fluxes is intensity and type of urban land-use. Considering different functional land-use urban areas can be subdivided into three contrast functional zones: recreational, residential and industrial. High amount of contrast functional zones and diversity of their combinations create conditions for extremely high spatial-temporal variability of $C0_2$ emission in urban areas.

There is lack of clear understanding of the impact that anthropogenic pressure has on soil respiration. There are evidences of both negative (Zhang et al., 2010) and positive correlation between soil respiration and the level of anthropogenic influence (Yuangen, 2001; Liao et al., 2010) or absence of any correlation between these parameters (Ohya, 1988). The current study aims to improve the understanding of $C0_2$ emission from soils with different level of anthropogenic impact and its spatial-temporal variability for the case study of Moscow city.

Objects and methods

Moscow city is a historical centre of Moscow region and European part of Russia (55° 45' N, 37° 37' E.). The territory of the city belongs to the south-taiga vegetation zone, however natural vegetation was mostly substituted by introduces species: maple, lime, poplar etc. A significant part of non-sealed areas covered with green lawns. Initially soil cover of the territory included sod-podzolic soils with elements of peat soils. So far, the natural soil cover remains only in natural parks, reserves and botanical gardens. Predominant part of the current soil cover is occupied by various urban soils: urbanozems, technozems, ecranozems and urban constructed soils (Prokofieva and Stroganova, 2004). Moscow city was founded in 1148. By 2010 the total city area exceeded 1000 km^2, constantly populated by more than 10,5 million of citizens. Considering population density Moscow city is one of the most urbanized areas in the world, thus it is a promising case area for the current research.

The first group of background objects has been investigated at the Forest Experimental Station (FES) of the Russian Timiryazev State Agrarian University (RTSAU) situated in North Administrative district of Moscow (fig. 1) with total area around 240 hectares. By its relief it is part of smooth moraine hilly plain typical for the big southern slope of the Klinsko-Dmitrovsky undulating ridge.

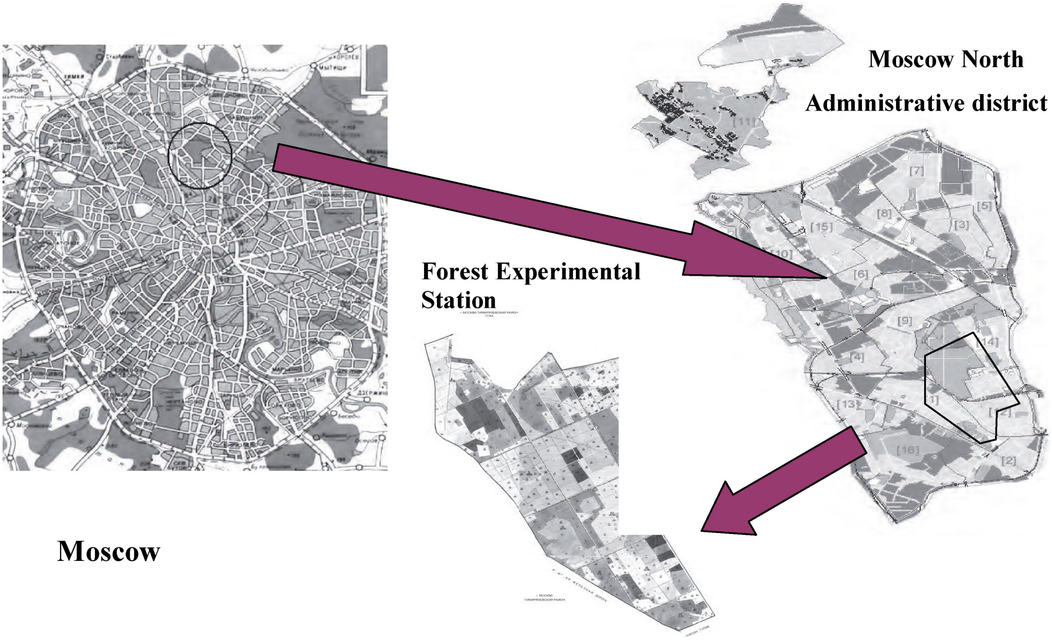

Fig. 1 . The arrangement scheme of RTSAU Forest Experimental Station

The climate of the area is characterized by the average July temperature of 19,1°C, average January temperature of -14°C, and the average annual precipitation close to 550 mm. Most widespread woods are pine, lime, birch, maple, oak, elm, larch. Rowan, chestnut, bird cherry tree, euonymus, hazel and gaiter-tree prevail in underbrush (Forest..., 2010). Regular supervision has been conducted over wood plantings and natural ecosystems since 1862. Last years are characterized by activization of versatile soil-ecological researches with especial attention on $C0_2$ emission (Vasenev et al., 2007; Vasenev, Raskatova, 2009).

Five background key sample plots are situated along the forest transect line passed through the smooth watershed hill with locations at the top of the smooth hill, its 2 slopes with different exposition, form, steepness, and their foots (fig. 2).

The 6-year $C0_2$ emission monitoring has been done monthly (replication 5) by alkaline method of Kar-

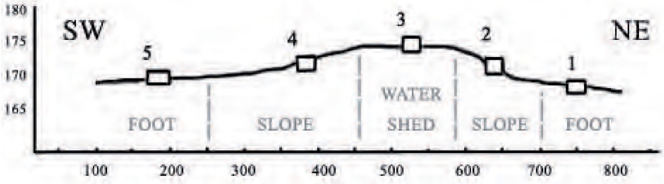

Fig. 2. The profile of FES transect line

pachevskiy version (The theory..., 2007) with topsoil regime analysis for soil moisture, temperature, bulk density, pH_{H20} and pH_{KC1} (replication 3). Annual investigation of humus content by Turin method, cation-exchange capacity and hydrolytic acidity by Kappen one, mobile forms of P and К by Kirsanov method (The theory..., 2006) has been done at the beginning of August with replication 3 too.

The second group of man-changed urban soils has been investigated in 2010-2011 at the representative set of urban landscapes, situated in all three landscape districts of the city (Right-bank, Left-bank and River-valley of Moscow river) - in order to learn anthropogenic impact on $C0_2$ emission from urban soils and its principal variability in Moscow city. For each district soil samples from recreational, residential and industrial zones were taken with 3 plots from each zone. Mixed samples were taken from both topsoil (0-10 cm) and sub-soil (10-150 cm). In the sampled soils microbial respiration was measured by basal respiration approach in standardized conditions (7 days pre-incubation with 70% of water capacity and 21°C, pure water added) (Anderson, Domsch, 1978) using gas chromatographer.

Results

Investigated Forest Experimental Station is characterized by smooth relief with prevalence of feebly marked moraine hill overlaid from surface by 40-cm layer of tegumental silt loam (key sample plot KSP # 3 - see Fig. 2). There are medium-soddy deeply podzolic surface gleyey silt loam soils on moraine clay loams (sod-podzolic soil subtype of podzolic type according to RF soil taxonomy). There is domination of oak and lime in 1-t synfolium with the highest value of grass common projective covering (70%) through the investigated ecosystems.

The same subtype soils are dominated on the northeast slope with steepness around 3° and its foot (key sample plots 2 and 1 - see Fig. 2) on the moraine clay loams and sandy loam fluvioglacial sediments, respectively. There is domination of maple and lime in 1-t synfolium on the slope and pine and lime in 1-t synfolium on the foot - with grass common projective covering around 50%.

The southwest gentle weakly concave slope with the increased length gradually passes into the foot and is characterized by the medium-soddy deeply podzolic surface gley silt loam soils on the moraine clay silt loams (sod-podzolic surface-water gley soil subtype of podzolic type). This landscape is characterized by prevalence of pine in 1-t synfolium with elm emergent on slope. The grass common projective covering varies from 60% on the slope to 40% on the foot.

The topsoil's horizons ($Al\text{-}AlA2_{(h)}$) are characterized by essential spatial variability and relatively (for sod-podzolic soils) high humus content (table 1). The soils on all key sample plots are very acid (according to hydrolytic acidity H_h values) with essential slope-target differences in basic cation contents within near the same cation exchange capacity around 21 me per 100 g that is typical for humus-accumulative horizons of loam sod-podzolic and sod-podzolic surface-water gley soils at the Central region of European territory of Russia (CRETR).

The content of main nutritious elements (alkaline-hydrolysable N, exchange К and mobile P) is low as common feature for forest podzolic soils at the CRETR. Their spatial variability can have the good correlation with mesorelief forms (NJ, nature of subsoil (mobile P) or less good - with their combination (exchange K). The spatial variability of investigated topsoil bulk density depends first of all from soil horizon texture and then from humus content and its form.

Investigated by alkaline method soil $C0_2$ emission showed its good dependence from soil moisture which has strong seasonal and interseasonal dynamics and essential variability

Table 1

The results of topsoil physicochemical analysis of FES key sample plots

(average data for 3-5 repetition)

Characteristic	KSP 1 NE foot	KSP 2 NE slope	KSP 3 top hill	KSP 4 SW slope	KSP 5 SW foot
Humus (%)	3,58	2.34	2,17	2,80	3,21
H_h, me per 100 g	12,4	11,4	12,4	16,4	14,6
Ca^{2+}+Mg^{2+}, me per 100 g	8,56	9,40	8,45	5,35	6,48
N_{ah}, mg kg^{-1}	155	98,0	90,3	113	129
P_2O_s, mg kg^{-1}	18	21	31	33	37
K_20, mg kg^1	88	71	91	103	102
Bulk density, g cm ^{3}	1,08	1,01	1,04	0,98	0,98

within monitoring landscape of Forest Experimental Station (table 2). The general matrix of monitoring results has significant variability due to contrast weather conditions during the observation period. For example, 2009 year was moist and rather cool in Moscow.

Table 2

Soil regime monthly monitoring data of FES key sample plots (average data for 3 repetition)

Key Sample plot	Year	Moisture, %					Soil temperature, °C					$C0_2$emission, kg/ha h				
		V	VI	VII	VIII	**M**	V	VI	VII	VIII	**M**	V	VI	VII	VIII	**M**
KSP 3 top hill	2009	31,0	30,3	24,6	20,0	***26,5***	10,1	12,2	16,0	16,1	***13,6***	42,0	26,8	15,8	11,2	***24,0***
	2010	27,1	20,6	14,9	7,42	***17,5***	13,8	16,6	21,8	25,2	***19,4***	39,4	21,4	8,2	5,8	***18,7***
	2011	26,3	17,7	19,9	13,8	***19,4***	11,8	13,3	17,8	19,0	***15,5***	36,1	16,8	13,1	12,0	***19,5***
	M	**28,1**	**22,9**	**19,8**	**13,7**	*21,1*	**11,9**	**14,0**	**18,5**	**20,1**	*16,1*	**39,2**	**21,7**	**12,4**	**9,7**	*20,7*
KSP 2 NE slope	2009	37,9	27,9	16,9	22,7	***26,4***	7,5	12,5	15,7	18,1	***13,5***	42,0	16,3	15,2	10,2	***20,9***
	2010	22,9	22,1	13,2	7,38	***16,4***	12,9	15,6	20,1	23,4	***18,0***	22,3	13,0	13,1	6,1	***13,6***
	2011	27,3	25,1	17,2	14,9	***21,1***	13,0	14,8	18,5	18,5	***16,2***	27,4	14,2	16,0	12,9	***17,6***
	M	**29,4**	**25,0**	**15,8**	**15,0**	*21,3*	**11,1**	**14,3**	**18,1**	**20,0**	*15,9*	**30,6**	**14,5**	**14,8**	**9,7**	*17,4*
KSP 1 NE foot	2009	40,9	34,8	18,2	19,5	***28,4***	7,1	11,5	14,1	15,2	***12,0***	44,0	23,4	8,2	11,7	***21,8***
	2010	28,7	24,4	19,0	8,19	***20,1***	11,7	13,5	17,9	22,6	***16,4***	37,1	22,7	12,4	7,4	***19,9***
	2011	26,9	16,6	19,9	18,8	***20,6***	12,4	14,0	16,2	16,2	***14,7***	32,0	18,9	14,6	13,9	***19,9***
	M	**32,2**	**25,3**	**19,0**	**15,5**	*23,0*	**10,4**	**13,0**	**16,1**	**18,0**	*14,4*	**37,7**	**21,7**	**11,7**	**11,0**	*20,5*
KSP 4 SW slope	2009	29,0	27,4	23,4	21,9	***25,4***	9,8	12,1	16,4	16,2	***13,6***	33,6	29,2	20,3	9,8	***23,2***
	2010	27,5	24,0	18,4	7,16	***19,3***	13,2	16,2	21,0	24,0	***18,6***	31,1	20,1	12,5	5,4	***17,3***
	2011	32,2	23,8	18,1	16,1	***22,6***	13,8	14,9	18,4	21,2	***17,1***	33,0	21,1	16,5	8,6	***19,8***
	M	**29,6**	**25,1**	**20,0**	**15,1**	*22,4*	**12,3**	**14,4**	**18,6**	**20,5**	*16,4*	**32,6**	**23,5**	**16,4**	**7,9**	*20,1*
KSP 5 SW foot	2009	34,3	32,5	19,9	13,8	***25,1***	8,5	12,4	14,9	16,2	***13,0***	48,3	29,2	15,2	12,9	***26,4***
	2010	27,2	25,8	14,0	9,96	***19,2***	12,1	14,0	18,7	23,7	***17,1***	32,6	23,5	11,6	6,1	***18,5***
	2011	33,7	19,9	20,1	17,4	***22,8***	13,6	14,8	18,8	19,5	***16,7***	40,4	20,7	16,5	14,1	***22,9***
	M	**31,7**	**26,1**	**18,0**	**13,7**	*22,4*	**11,4**	**13,7**	**17,5**	**19,8**	*15,6*	**40,4**	**24,5**	**14,4**	**11,0**	*22,6*

2010 year is characterized by unusual dry and hot July and August. 2011 year was typical for the region but its soil moisture regime had essential consequences from previous year dry summer season, that apparently influenced on biological activity of soils too.

Typical for all monitoring years most active $C0_2$ emission in the beginning of vegetation season can be result not only maximum soil microbial activity but also plant seeds and roots respiration in the beginning of their vegetation. During the season soil $C0_2$ emission is gradually decreased due to moisture changes. The same regulations have been shown obviously in case of interseasonal dynamics of average data for all investigated ecosystems of Forest Experimental Station too (fig- 3).

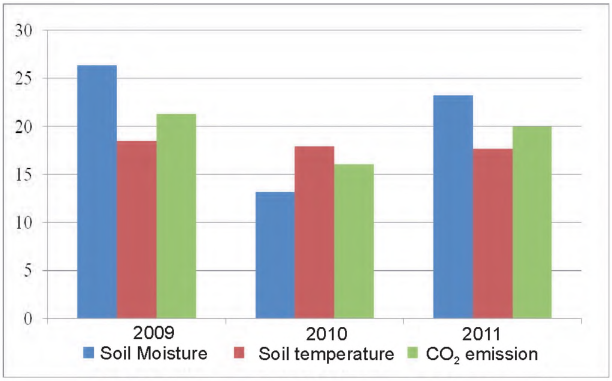

Fig.3. The interseasonal dynamics of monitoring average data of topsoil moisture, temperature and $C0_2$ emission in the investigated ecosystems of the Forest Experimental Station

Interesting that during all observed seasons soil CO, emission was usually affected by soil moisture more then by temperature that may be common for this type of forests - especially in case of year with dry summer season (fig. 4) the number of which must be increased in nearest future due to climate global change. The temperature influence on soil $C0_2$ emission has significant values of regression only in case of year with normal precipitation conditions (fig. 5).

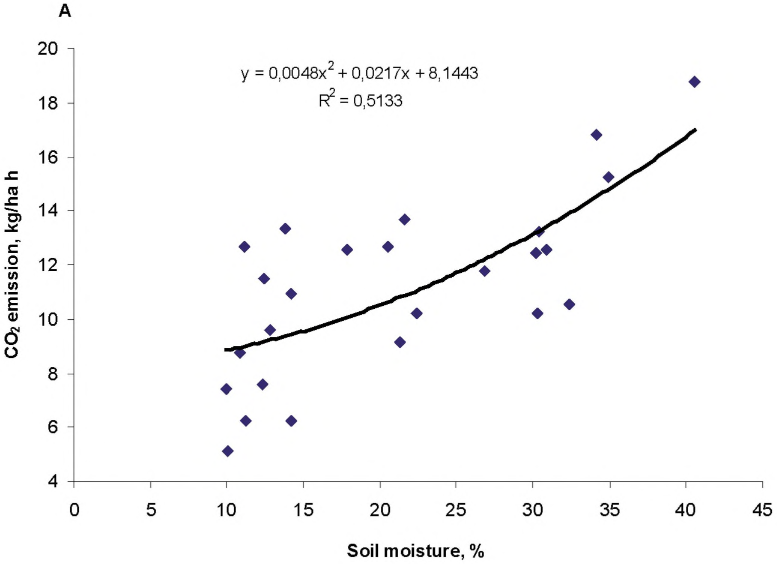

Fig. 4. The regression analysis of topsoil moisture influence on $C0_2$ emission seasonal dynamics in the investigated ecosystems of the Forest Experimental Station

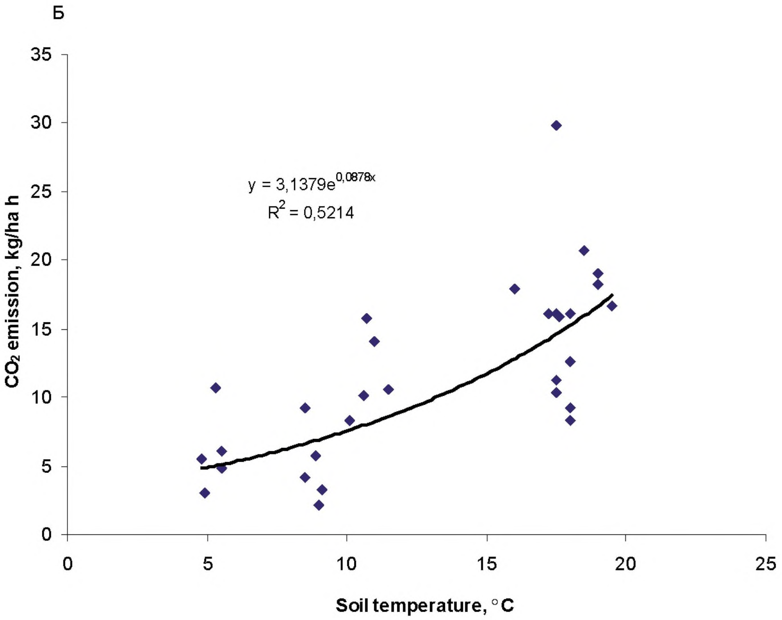

Fig. 5. The regression analysis of topsoil temperature influence on $C0_2$ emission seasonal dynamics in the investigated ecosystems of the Forest Experimental Station (in case of normal precipitation year)

The conducted researches have shown increased spatial variability of soil regime parameters even within low-contrast elements of mesorelief that probably is typical for mature forest ecosystem. Under condition of transient landscape type (between taiga and temperate broadleaf forest) even not so significant changes of slope steepness (1-2°), its form (from straight to weakly concave) and length (from 200 to 400-500 meters) result in qualitative changes of soil $C0_2$ emission due to essential changing in soil moisture, forest features and microbiological activities.

The spatial variability investigation in scale of city by basal respiration approach has shown the essential changes of microbial respiration from 0.15 (River-valley district, industrial zone - 3) to 1.86 $C0_2$-C g^{-1} of soil h^1 (Right-bank district, recreational zone-2) for the topsoil and from 0.10 (Right-bank district, residential - 5) to 1.24 $C0_2$-C g^{-1} of soil h^1 (Right-bank, recreational -1) for the subsoil observed. In average microbial respiration for the topsoil wasn't significantly different from one for the subsoil: 0.53 and 0.35 g^{-1} of soil h^1 correspondingly. Maximal average topsoil $C0_2$ emission value was obtained for right-bank district, whereas the minimal one was shown for river-valley district. The same pattern was shown for the subsoil (fig. 6).

However, the difference between microbial respiration from right-bank, left-bank and river-valley districts were not significant neither for topsoil nor for subsoil observed. As for the functional zones, the highest microbial respiration values were shown for recreational areas, whereas the lowest - the residential ones in case of topsoil and industrial - in case of subsoil. Although the difference between functional zones was not significant for the subsoil, microbial respiration obtained for the recreational areas was significantly higher than for residential and industrial ones in case of topsoil (table 3).

High spatial variability of $C0_2$ emission was shown by standard deviation values, achieving 50% from the mean values. The highest standard deviation was shown for recreational areas both for topsoil and subsoil. In order to analyze factor, influencing microbial respiration of urban soils three-way ANOVA was used. The following factors were studied: depth, functional zone and landscape district. Depth and functional zone factors were demonstrated to have the predominant impact on $C0_2$ emission variability, distinguishing 18 and 11% of total variance correspondingly (table 4). Determination coefficient (R^2 = 0.37) demonstrates average prediction power of the model. Thus not all possible influencing factors were included to the model.

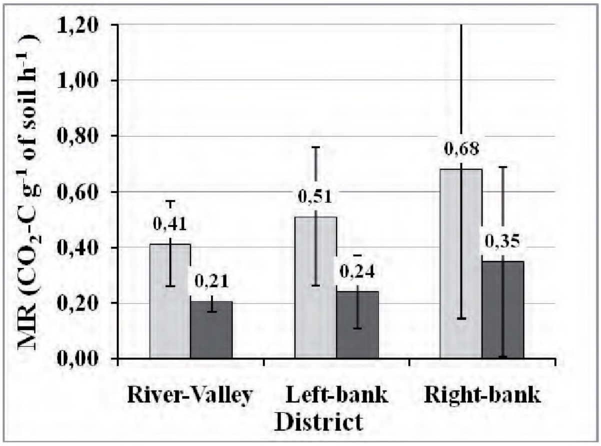

Fig. 6. $C0_2$ emission from urban soils in different landscape districts of Moscow (by basal respiration approach)

Table 3

Microbial respiration from soil in different functional zones

Functional zone	Topsoil (mean ± sd)	Subsoil (mean ± sd)
Industrial	0.41 ± 0.25 ***a***	0.27 ± 0.09 ***a***
Residential	0.39 ±0.08 a	0.22 ± 0.10 ***a***
Recreational	0.80 ± 0.47 b	0.31 ± 0.35 ***a***

a, b - homogeneous groups (LSD-test).

Table 4

ANOVA **results** (n = 54)

Factor	F	p-level	%
District	2.76	0.07297	7.3
Zone	4.50	0.01609*	11.8
Depth	13.55	0.00058*	17.8

* Significant factors (a<0.05).

Discussion

Urban soils possess extreme spatial variability that results in high heterogeneity of their basic properties, regimes and functions.
We've shown extremely high temporal and spatial variability of soil respiration, measured by alkaline method and basal respiration approach in background forest and urban soils of Moscow city. This corresponds to a few reported in literature results for USA and European cities (Kaye et al., 2005). High spatial variability of $C0_2$ emission from urban soil can be explained by contrast factors, influencing them: contrast moisture and temperature regime, various pollution level, high amount of comparatively small in size, but contrast in features functional zones.

Higher respiration values shown for the topsoil in comparison to the subsoil corresponds to traditional assumption of microbial distribution with depth with the maximal amount in top layers, shown both for urban and natural soils (Ananyeva et al., 2008). However demonstrated ratio between topsoil and subsoil microbial respiration in urban soil is much higher than one in natural ones (Vasenev, 2011), that can be explained both by active mixing urban soil profile during construction and by the phenomena of "cultural layer'.

The concept of cultural layer originates in archaeological research, where it was used to define the age of artifacts and describe the settlement history. Afterwards cultural layers of several ancient Russian towns were studies as a part of soil morphological research. Cultural layers and soils buried under them were shown to be a single complex, developing in time. A number of specific soil features were described for cultural layers: high level of heavy metals' accumulation and soil microbiological communities, non-typical for topsoil.

From $C0_2$ perspective cultural layers, including wooden remains, coal and buried non-urban horizons (Prokofieva and Stroganova, 2004) and soil organic carbon up to 3-5% represent conserved carbon stocks with a high potential to emit. Thus there is no surprise that average $C0_2$ emission from urban subsoil is considerably higher than for the natural ones.

Comparison of two analyzed factors: landscape district and functional zone demonstrated that for the case of urbanized ecosystems anthropogenic influence on $C0_2$ emission from soil is higher than the impact of internal natural landscape heterogeneity. No significant difference was shown for various landscape districts, whereas the impact of functional land-use was significant. Soil respiration in recreational zones was significantly higher than in residential and industrial that proves the pattern of microbial respiration decline with anthropogenic pressure increase (Ananyeva et al., 2008; Vasenev, 2011).

The conducted researches have shown high spatial and temporal variability of background forest soil $C0_2$ emission that must be taken into attention during procedures of planning and interpretation of urban ecosystem and soil monitoring data for which intraurban forests is usually considered as local "standard” objects without special analysis of their inherent variability and dynamics.

Under condition of transient between zonal and province landscape type even smooth mesorelief forms able to create essential differences in soil and ecosystem regimes and particularly in soil $C0_2$ emission which is integral indicator of soil microbiological and plant roots activities. Investigation of this phenomenon in case of regionally and functionally representative landscapes allow to increase essentially the accuracy of information scale-transfer modules and GIS-based ecological models in demand for environmental impact assessment and decision support system making and adapting to concrete project issues.

Conclusion

$C0_2$ emission from urban soils in Moscow city is extremely variable in space, mainly as a result of contrast functional land-use history and practices. In general, soil respiration declines with anthropogenic pressure increase. However, urban soils demonstrate high potential to emit carbon, mainly referring to subsoil.

Shown by these researches high spatial and temporal variability of background intraurban forest soil $C0_2$ emission lias important methodical and applied consequences. It must be taken into attention during procedures of planning and interpretation of urban ecosystem and soil monitoring data as well as of environmental impact assessment and decision support system making based on local “standard” objects.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ ОСНОВНЫХ ФАКТОРОВ ПРОСТРАНСТВЕННО-ВРЕМЕННОЙ ИЗМЕНЧИВОСТИ ЭМИССИИ $C0_2$ ИЗ ГОРОДСКИХ ПОЧВ МОСКВЫ С РАЗЛИЧНЫМ УРОВНЕМ АНТРОПОГЕННОЙ НАГРУЗКИ НА НИХ

Аннотация: в статье представлены основные результаты сравнительного анализа основных факторов пространственно-временной изменчивости эмиссии $C0_2$ из городских почв Москвы с различным уровнем антропогенной нагрузки, которые характерны для экосистем Московского мегаполиса. Основной ряд объектов включает природные дерново- и торфянисто-подзолистые почвы Лесной опытной станции РГАУ-МСХА имени К.А. Тимирязева, урбаноземы и конструктоземы различных функциональных зон города.

Ключевые слова: глобальные изменения, городские экосистемы, лесные экосистемы, мониторинг выбросов СО-,, пространственная изменчивость, временная динамика, базальное дыхание, экологические модели.

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