

BASAL RESPIRATION AS A PROXY TO UNDERSTAND SPATIAL TRENDS IN CO₂ EMISSIONS IN THE MOSCOW REGION

**V.I. Vasenev¹, J.J. Stoorvogel², V.G. Plyushchikov¹,
N.D. Ananyeva³, K.V. Ivashchenko^{1,3}, O.N. Romzaykina¹**

¹RUDN University
Miklukho-Maklay str., 8/9, Moscow, Russia, 117198

²Soil Geography and Landscape Group, Wageningen University
P.O. Box 47, The Netherlands, 6700 AA, Wageningen

³Institute of Physico-chemical and Biological Problems in Soil Science, RAS
Institutskaya str., 2, Pushchino, Moscow region, Russia, 142290

Soil respiration (Rs) is an important terrestrial CO₂ efflux and receives significant attention at different scale levels. However, the sampling density is limited and global Rs databases are biased towards natural ecosystems. Urbanization is among the most important current land-use trends and its role will likely grow in the future. Urban soils store considerable amount of carbon and are very heterogeneous and dynamic, which affects Rs. Our understanding of the Rs spatial variability is limited, especially for the regions with heterogeneous bioclimatic conditions and high urbanization level. The methodological constraints of direct Rs measurements in the field limit the number of observations. As an alternative approach to approximate the spatial variability of Rs, we used basal respiration (BR) as an indirect measurement. We implemented digital soil mapping technique to map BR as a proxy of Rs in a heterogeneous and urbanized Moscow Region. Topsoil and subsoils BR maps were developed for the region and spatial variability per land-use and soil type was analyzed. BR averaged for the urban areas was lower than in forests and meadows, however, urban areas became the hotspots of BR's spatial variability in the region. Considerable contribution of subsoil layers to the total BR was also found with the maximal 30% contribution in urban soils. Although the absolute levels of respiration remained uncertain, the spatial patterns of BR are likely to correspond well with Rs patterns, determined by soil type, land use and allocation of urban areas.

Key words: urban soils, soil functions, microbial respirations, urbanization, digital soil mapping

1. INTRODUCTION

Soil respiration (Rs) causes an annual efflux of 80 Pg carbon to the atmosphere and is the largest carbon efflux of terrestrial ecosystems [49; 9]. This efflux is almost ten times that released by fossil-fuel emissions [45]. The CO₂ emissions by Rs are therefore likely to have a large influence on global climate. At the same time Rs impacts local soil quality. Therefore, the temporal and spatial patterns in Rs need to be well understood to assess changes in soil functions and ecosystem services [10; 15].

Rs depends largely on a range of soil abiotic and biotic parameters [13; 20]. Soil temperature, moisture regimes, and soil organic carbon (SOC) concentrations are considered to be the principal driving factors behind the local spatial variability of Rs [62; 32]. Regional and global Rs variability is typically represented by average Rs rates for different land-uses and soil types [45; 22; 24; 2]. So far, the spatial heterogeneity of Rs

remains inadequately understood [54; 29]. In order to get a better understanding of Rs variability for a region, spatial patterns need to be described.

Studies on Rs variability often focused on natural and agricultural ecosystems [e.g. 26; 22; 33; 30]. Urban areas received very limited attention. Due to a number of specific factors and conditions, like soil sealing and zoning [48; 43], a very different spatial variability can be expected. Smooth changes in natural and agricultural ecosystems are substituted by a highly variable patchwork of zones with strict boundaries [56]. Urban ecosystems therefore require a specific approach to analyze the spatial distribution of Rs.

The most common approach to determine Rs is based on direct field methods where the CO₂ efflux from the soil surface is measured *in situ* and indirect methods where Rs is predicted based on auxiliary information or where Rs is measured under standardized conditions. Direct methods include conventional alkali absorption techniques [12] and a variety of chamber approaches (open-path, closed-path, and dynamic close chambers) [37; 5; 47]. They are widely used to study the temporal (diurnal or seasonal) dynamics in Rs, normally as a response to changes in soil temperature and moisture conditions. To apply this approach for larger regions, the study area is stratified (e.g. based on soil or land-use type) with chambers installed at a limited number of representative sites [39; 31]. By relying on these representative sites, the spatial variation within each strata is not considered. Whether direct measurements give satisfactory results in large and heterogeneous areas with a large number of different natural, rural, and urban ecosystems is questionable. Alternatively, the spatial variability of Rs can be analyzed indirectly through a relatively easily measured proxy variable, which allows for a larger number of observation points.

Basal respiration (BR) is such a proxy. BR is defined as the steady rate of soil respiration, which originates from the mineralization of organic matter [42]. Together with soil microbe biomass, BR is a commonly accepted indicator to quantify changes in the activity of the soil microbial community and soil quality [61; 6]. BR is determined by measuring CO₂ produced by soil microorganisms after pre-incubation under standardized temperature and moisture conditions [3; 15]. BR thus characterizes the potential soil CO₂ emissions by microorganisms under the optimal conditions rather than the actual carbon efflux. Since the experimental conditions are standardized, the initial effect of field temperature and moisture regimes is eliminated [8]. As a result it allows for the comparison of different samples (e.g. taken at different locations or moments in time). Monitoring over a long periods is less important and many more samples can be taken throughout a region of interest with all the different strata.

This study implements BR as a proxy to understand the spatial heterogeneity of soil respiration in large, diverse and highly urbanized Moscow Region. So far, spatial patterns in Rs in this region remain poorly understood if one compares them with the EU and USA, where Rs is continuously measured through FLUXNET [60; 4].

2. MATERIALS AND METHODS

2.1. Moscow Region

Moscow Region extents over 46,700 km². The territory of the Moscow Region has a plain relief ranging from 100 meters in the east to 300 meters above sea level in the north and west. The region has a temperate continental climate. Its mean annual tempera-

tures range between 3.5 °C to 5.8 °C. Average annual rainfall varies from 780 mm in the north to 520 mm in the south. In winter, average daily temperatures normally drop to approximately –10.0 °C, though there can be warm periods with temperatures rising above 0.0 °C. The average number of days with temperature below zero varies between the north and the south and between years, and averages between 130 and 190 [50; 38]. Parent material includes moraine loam and clay in the north and center, fluvio-glacial sands in the east and west, and cover loam in the south. Vegetation varies with climate and includes three main bioclimatic zones: south-taiga, deciduous forests and steppe-forest) [50]. Soils include Orthic Podzols in the north, Eutric Podzoluvisols in the center, Orthic Luvisols and Luvic Chernozems in the south, Dystric Histosols in the East, and Eutric Luvisols in the flood-plains of the Moskva and Oka rivers [16; 17; 51]. Anthropogenic landscapes (agricultural, fallow-, and urban lands) occupy nearly 60% of the territory. The urban area is rapidly increasing and currently occupies more than 10%, including 68 cities and towns with 18.8 million inhabitants (including Moscow city). Moscow is the largest European city with a population of over 11.2 million people.

2.2. Analyzing spatial variability in basal respiration in the region

Soil sampling

In order to consider both natural and urban-specific factors in the region and to provide necessary data for digital soil mapping (DSM), a stratified sampling design was implemented that represents the variability in bioclimatic conditions and consider short-distance variability within the settlements. Sampling points were chosen in Moscow city and six settlements in the region in such a way that traditional (zonal soil type and land-use type) and urban-specific factors (functional zoning, age and size of the settlement) were considered. Inside the towns, samples were taken from different functional zones including industrial, residential and recreational zones. We also sampled forest, cropland and meadow areas outside the towns for comparison. In total 211 locations were observed (Fig. 1).

Inside each stratum, sampling plots were selected randomly. For each plot, 5 top-soil (0–10 cm) samples were taken from a 2 m² square plot (corners and center) and pooled into a single composite sample. A single sample was taken from the subsoil (10–150 cm) at the center of the plot. Considering the variability of regional soil conditions including the Luvic Chernozems with thick humus accumulation layers, likely contributing to BR, we expanded the subsoil included into the analysis to 10–150 cm. Considering budget limitations and the necessity to expand the sampling area to capture different factors of BR spatial variability in the Moscow Region for DSM approach, subsoil layers from 10 to 150 cm deep were mixed into a single sample per point. This gives an idea of the subsoil contribution to total microbial respiration. As far as we know, this has never been done at the regional level. However, it does not provide insight on the profile distribution of BR.

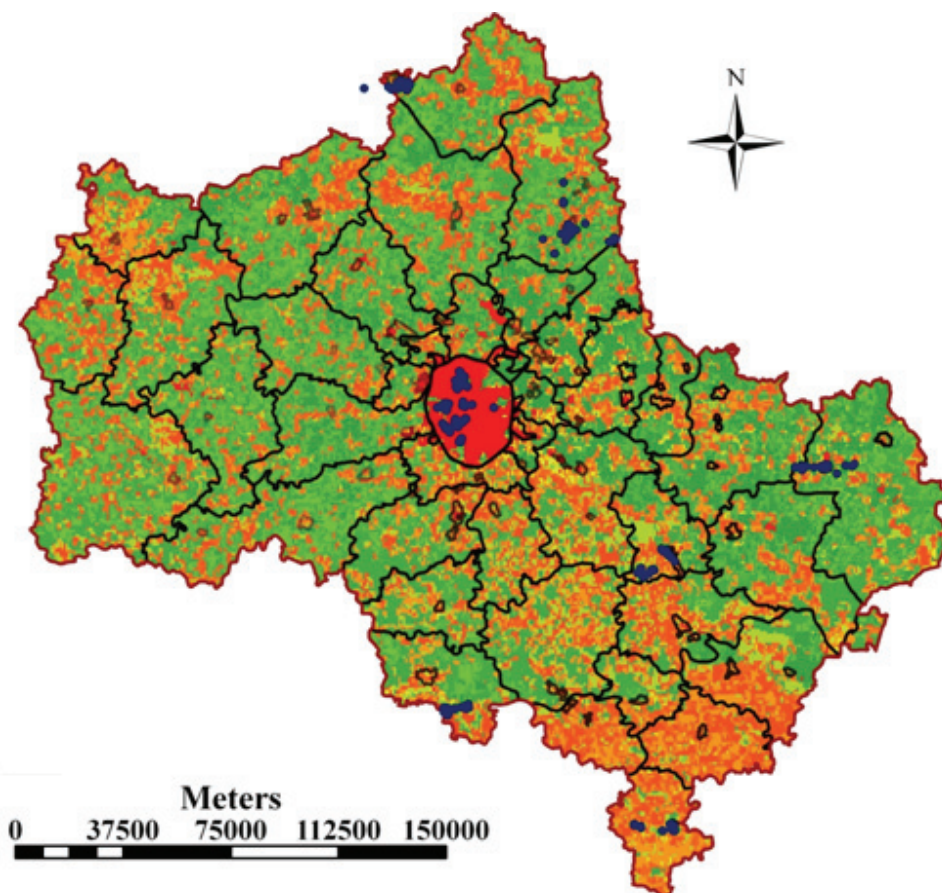


Figure 1. The level of urbanization in Moscow region ranging from natural (green) to urban (red) with the location of the observation points

Samples were sieved (2 mm) at the natural moisture content and all the fine plant root residues were removed. Due to geographical location and geomorphological features of the region with a plain relief and domination of loamy and clay parent material stone inclusions in soil are very rare, thus stoniness was not considered in the estimation of soil features including carbon stocks. At the same, we faced anthropogenic inclusions (bricks, concrete flags and service tubes) in the urban areas, which did not allow to sample up to the 150 cm depths at some points. To consider this we implemented correction coefficient on cut-off profiles when estimating BR in urban subsoil.

Mapping BR and analysis of variability

A DSM approach was implemented to map BR as a function of traditional (relief, climate, land-use, vegetation and soil type and complexity) and urban-specific (functional zoning, size and age of the city) factors. Since a strong correlation between SOC and BR is widely assumed and was reported for different ecosystems [3; 59; 2], the SOC content was also added as an explanatory variable, based on the 771 m resolution map of carbon contents and stocks derived for the region [58].

Land-use type, soil type, mean annual temperature, average annual precipitation, slope, normalized difference vegetation index (NDVI), and SOC content were used as explanatory variables in the natural and agricultural sites. In the urban areas urban-specific factors were added, including functional zoning (derived from NDVI), age and size of the settlements. Since only open (non-sealed) areas were included in sampling campaign, we considered BR estimation and mapping for impervious areas only. To achieve this we used correction coefficient, which was assigned as 0.90 for recreational zones and 0.50 for residential and industrial ones, based on the literature data and previous investigations for Moscow city and Moscow Region [57].

Normality of the distribution of BR values was checked by Shapiro-Wilk's W test and homogeneous of variances was checked by Levene's test. Since the regression kriging was not available due to the stratified sampling design, we implemented statistical general linear model (GLM), correlating BR to explanatory variables, to predict spatial patterns of topsoil and subsoil BR in the region. The GLM was obtained by a step-wise linear regression. The R^2 and R^2_{adj} were used to keep or remove explanatory variables and to characterize the predictive power of the model. Based on the GLM two separate maps for topsoil and subsoil BR were developed with the resolution of 771 m for the region. Details on the implemented mapping and GLM approaches were published in Vasenev et al., 2014. Statistical analysis was performed in Statistica 6.0 [11]. Visualization and GIS analysis was carried out in ArcGIS [23].

The BR approach does not give insight into the temporal dynamics of Rs, although it provides an explicit picture of the spatial distribution of Rs. In order to characterize the spatial variation of Rs for different ecosystems and biomes and also to compare results from BR approach with ones from in situ method we aggregated BR maps into the different strata, representing different combinations of distinguished traditional and urban-specific factors. In addition, the CV for each strata was estimated to characterize spatial variability of Rs. Maps with the CV of topsoil and subsoil BR were created for the Moscow Region.

3. RESULTS

3.1. BR in the Moscow Region

Modelled BR values for the entire Moscow Region showed a high spatial variability with averages of $0.75 \pm 0.57 \mu\text{g CO}_2\text{-C g}^{-1} \text{ soil h}^{-1}$ for the topsoil and $0.25 \pm 0.17 \mu\text{g CO}_2\text{-C g}^{-1} \text{ soil h}^{-1}$ for the subsoil. Spatial variability was similar for both layers. A significant positive correlation with SOC content was found for both layers ($p < 0.05$; $r = 0.43$ and $r = 0.37$ for topsoil and subsoil BR respectively). Land-use had an important impact on BR — the lowest values were obtained for urban areas, whereas BR for bogs and meadows was significantly higher than for all other land-use types. Different soil types presented different BR with the highest values for the Luvic Chernozems and lowest ones for Dystric Histosols and Eutric Luvisols. However, differences between soil types were not significant due to the large variability (Table 1).

Table 1

Basal respiration in Moscow region averaged over land-uses and soil types

Factor	N	Topsoil BR ($\mu\text{g CO}_2\text{-C g}^{-1}\text{ soil h}^{-1}$)			Subsoil BR ($\mu\text{g CO}_2\text{-C g}^{-1}\text{ soil h}^{-1}$)		
		mean	SD	CV (%)	mean	SD	CV (%)
<i>Land-use</i>							
Urban	46	0.64	0.45	69	0.27	0.20	74
Bogs	18	0.76	0.45	59	0.26	0.13	49
Arable	80	0.77	0.52	68	0.26	0.18	67
Forest	53	0.72	0.40	56	0.24	0.13	56
Meadow	13	1.11	1.41	128	0.20	0.21	107
<i>Soil type</i>							
eutric Podzoluvisols & dystric Histosols	108	0.76	0.50	66	0.28	0.20	70
eutric Luvisols	15	0.59	0.52	88	0.18	0.14	76
orthic Luvisols	43	0.73	0.41	55	0.24	0.13	55
luvic Chernozems	5	0.84	0.44	52	0.24	0.10	44
orthic Podzols	39	0.78	0.88	112	0.22	0.13	59

The spatial patterns differed between the topsoil and subsoil maps but patterns in BR corresponded to the patterns in soils and land-use for both. Topsoil BR was the highest in the east of the region with large areas occupied by bogs and Dystric Histosols. High topsoil BR was also found for the Orthic Podzols in the north and Luvic Chernozems in the south. Urban areas and especially the Moscow city showed high variation in topsoil BR with higher values in the green spaces and lower in the central built-up parts (Fig. 2 A). Subsoil BR followed the same trends. In general, subsoil BR was less variable than topsoil BR with the highest values found in the west with Eutric Podzoluvisols (Fig. 2 B).

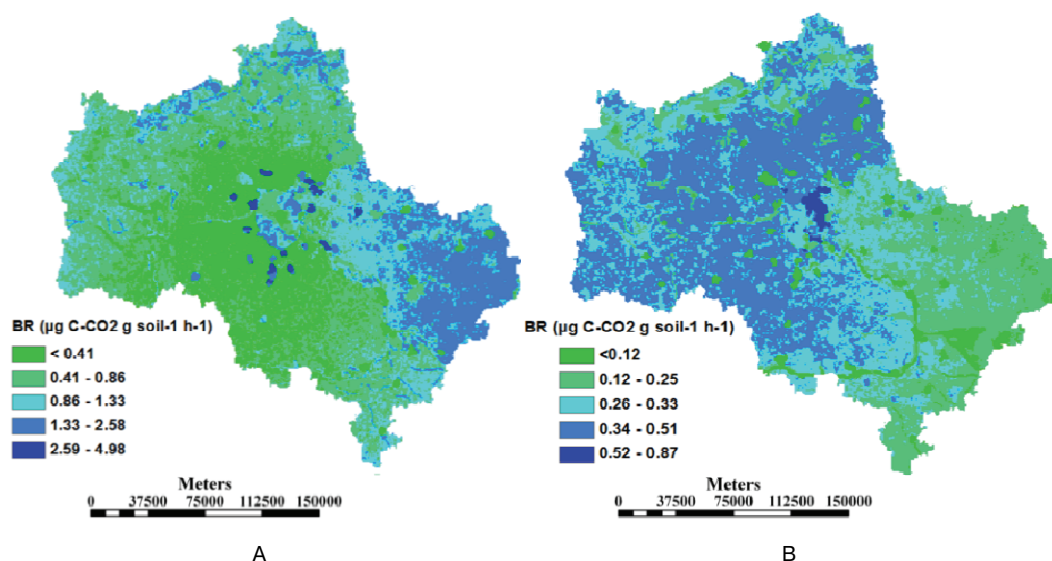


Figure 2. Basal respiration ($\mu\text{g CO}_2\text{-C g}^{-1}\text{ soil h}^{-1}$) of topsoil (A) and subsoil (B) in the Moscow Region

3.2. Mapping BR spatial variability in the region

The maps allowed for a better understanding of the spatial variability of BR for the region in general as well as for separate land-uses, soil types and their combinations. The highest variability was shown in urban areas and bogs with average CVs exceeding 100%. We observed this pattern for both soil layers, although subsoil BR was more homogeneous with averaged CV up to 50–60%. The highest BR variability among the soil types was found in the topsoil of the Orthic Podzoluvisols and the subsoil of the Dystric Histosols and Eutric Luvisols which can be explained by the large and heterogeneous areas where these soil types are found (more than 70% of the total area of the region). The coefficient of determination for the models was 0.51 and 0.38 for the topsoil and the subsoil correspondingly.

Analysis of BR averaged per land-use and soil type provides information on the factors influencing its variability but it does not give a clear picture of the spatial distribution. More valuable is to analyze spatial variability per different strata, representing interaction of various environmental and management conditions. In order to obtain this information we aggregated the BR maps based on the combinations of traditional and urban-specific factors distinguished for the modelling and estimated CV values per each stratum. The highest variability of topsoil and subsoil BR was reported for the urban areas, which was clearly represented by hotspots on the maps, coinciding with the borders of settlements. The CV obtained for topsoil BR in the urban areas varied from 40–50% for recent settlements (< 50 years) of small and middle size (< 100 000 citizens) to 70–100% in small ancient towns (> 500 years) and Moscow megapolis. The same pattern was found for the subsoil BR although the CVs were almost half. CV values in industrial and residential areas were 20–30% higher than in recreational zones for both topsoil and subsoil BR (Fig. 3).

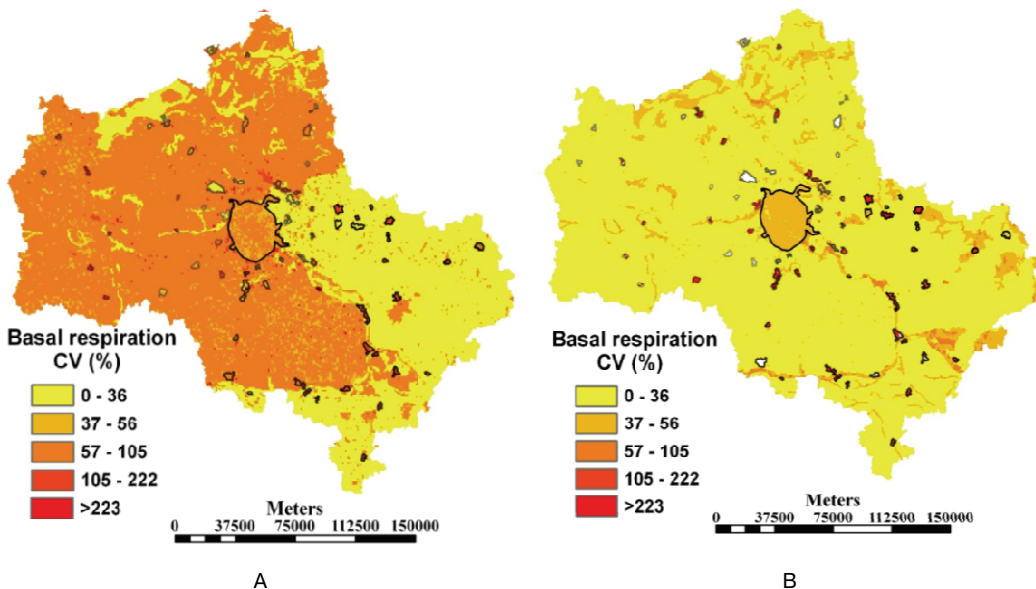


Figure 3. Coefficient of variance (CV%) of topsoil (A) and subsoil (B) basal respiration in Moscow region

4. DISCUSSIONS

4.1. Spatial variability of soil respiration in Moscow Region based on BR maps

BR observation for the Moscow Region in combination with DSM techniques resulted in 771 m resolution maps of topsoil and subsoil BR. As far as we know, this was the first attempt to analyze and map regional BR with this level of accuracy. The area of central Russia remains under-observed in many global assessment and databases of carbon stocks and fluxes [4; 9], thus the opportunity to evaluate our results based on ones from literature was very limited. Analysis, available at the country scale [40; 30] provides averaged values per soil type and land-use type, but lack the information of Rs's spatial variability within these clusters. Besides, this outcome is based on the direct extrapolation of point Rs data for the polygons of the 1 : 2.5 million soil map of Russia [18], thus uncertainty is very likely.

Patterns of BR between and within different soils types and land-uses were analyzed and showed a good correspondence with literature. All their studies report a significant negative correlation between soil microbiological activity and anthropogenic pressure levels. This was also confirmed by the results obtained at the test area. High topsoil BR values reported for Luvic Chernozems, Dystric Histosols and Orthic Podzols is in good coherence with SOC patterns described for the bioclimatic and soil zones in the region [50; 59] confirming the concept of BR as an indicator for respiration of soil organic matter — based microbes [15].

Different spatial variability described by CV for observed land-use types with the highest heterogeneity of BR in urban area also confirm existing opinion on high patchiness of urban environment [28; 56]. High variability of BR in urban areas is likely explained by the heterogeneous urban conditions that influence the limiting factors for soil microbiological communities: water and temperature regimes and nutrient contents. Several studies that report high spatial variability of C and N stocks in urban areas [27; 44; 35] indirectly confirm this outcome. We also found significant difference between topsoil and subsoil BR. In average for the region, BR in the topsoil was over four times larger with a more than double CV than subsoil BR. This corresponds to studies that indicate the major soil microbial community in the topsoil [74; 53]. However, 30% of the total BR in urban areas comes from the subsoil, which was higher than in croplands and meadows and comparative to forest. Considerable contribution of subsoil BR in urban areas refers to specific profile distribution of SOC in the settlement with high concentration not only in the surface, but also at a certain depth in the so-called “cultural layer” [1; 34; 57]. In general urban areas made the most significant contribution to the regional spatial variability of BR (vividly illustrated by red spots on the maps of the CV), which was the result of various urban-specific factors.

4.2. Uncertainties in BR maps of Moscow Region

Predictive power of the GLMs implemented for BR mapping estimated by $R_{adj}^2 = 0.51$ and 0.38 for topsoil and subsoil correspondingly indicates that 50 to 60% of total variability remained unexplained and thus the results are rather uncertain. Uncertainty

of the obtained results is coming from the experimental design and assumption taken in the GLM and BR estimations. Additional source of uncertainty came from the simplifications and assumptions taken in the modelling process. For instance we technically could not separate residential and industrial functional areas and thus used it as single unit, although literature and previous research showed a significantly lower BR in industrial areas compared to all the other forms of land-use [19; 55]. We also introduced reduction coefficient to consider impervious soils, however there are evidences in literature that soil sealing results not only in decrease of R_s at the sealed areas, but also in increase of CO_2 emissions from adjacent open territories [52; 48]. Comparison between topsoil and subsoil BR also was not straightforward since differences in sampling approaches and aggregating 10—150 cm subsoil in a single soil sample, which, considering known strong correlation between microbiological activity and soil depth, may provide very rough results. However, it gave us an opportunity to guess on the contribution of the subsoil to total respiration and its variability, that is often left out of regional analysis.

4.3. ADVANTAGES AND CONSTRAINTS OF BR AS A PROXY TO UNDERSTAND THE SPATIAL VARIABILITY OF SOIL RESPIRATION

Implementation of BR and DSM techniques provided an opportunity to analyze and map the spatial variability of regional soil respiration based on a limited number of observations ($n = 211$). This would not have been possible with the traditional *in situ* chamber approach. In addition, BR can provide information on the respiration in different soil layers, whereas direct field measurements normally refer to the surface layer. However, the BR as a proxy of soil respiration obviously has some constrains. The main one is coming from different mechanisms and processes underlying R_s and BR. Total R_s includes autotrophic respiration of root systems and root-associated organisms and heterotrophic respiration of free-leaving microorganisms in the soil [14; 20], whereas BR refers only for the heterotrophic component. Moreover, disturbing and pre-incubation procedures influence the CO_2 production by microorganisms [15] and makes comparison between absolute values of BR and *in situ* R_s rather challenging.

So, BR is rather questionable as a tool to measure actual R_s , however it is a good proxy to understand the spatial variability. Recently, for many applications, including regional carbon sequestration assessment and climate mitigation analysis and modelling, understanding the R_s 's spatial variability becomes essential. BR is probably the best option for spatial analysis, since direct measurements are not applicable and remote sensing approach predict R_s mainly based on the vegetation indexes [25] and thus much less related to the soil processes. The relevance of BR as a proxy is confirmed by significant predictive power of the developed models ($R^2 = 0.51$ and 0.38 for the topsoil and subsoil respectively). This result is comparative or better than some regional models of soil carbon stocks modelling [36].

5. CONCLUSIONS

Soil respiration (Rs) is an important terrestrial CO₂ efflux. Although the most comprehensive global Rs database [9] contains many respiration records, this dataset is still biased towards natural ecosystems and towards the USA and EU. This doesn't improve understanding of Rs's spatial variability. The methodological constraints of Rs measurements in the field likely limit the number of observations, especially in regions where scientific equipment and technology is poorly available.

We implemented indirect measurements of basal respiration (BR) to capture spatial variability of soil respiration for the Moscow Region. This relatively simple approach expanded the regional sampling scheme and formed the basis for mapping of BR for the Moscow Region. We digitally mapped soil BR as regional Rs proxy. Although our absolute BR remain uncertain, the BR spatial variability, however, corresponded well with one measured directly. Land use was a major factor determining the spatial heterogeneity of the regional soil respiration. Most of variation was coming from urban areas.

Soil respiration is currently getting increased attention as an important source of CO₂ emission, indicator of soil health and quality. Due to very high variability in space, following bioclimatic conditions and land-use change, understanding spatial trends of Rs gets even more important than more traditional estimation of averaged emission. Direct measurements of in situ Rs at the limited areas with further extrapolation regionally and globally don't correspond to the demand in spatially explicit information, highlighting necessity in alternative proxies. Our implementation of BR approximates this spatial variability and will considerably improve understanding of soil respiration patterns, especially for regions where direct measurements are unavailable. Although our result represent a preliminary study they contribute to implement our understanding of CO₂ emissions from urban soils and [21; 41] and provide evidence that the contribution of urban soils to regional carbon balance will be progressively more important in the future when urbanization and pollution will be among the most important factors affecting soil quality and health.

Acknowledgements

The project was partly supported by RFBR projects № NK 15-54-53117 and № NK 15-34-70003 and the Wageningen University Sandwich Fellowship Program. The authors thank Ilya Mazirov, Anna Shchepeleva and Pavel Lakeev for assistance with the field measurement, Julia Sotnikova and Dmitry Sarzhanov — for help with soil chemical analysis and Rik Leemans and Ivan Vasenev for valuable suggestions.

© V.I. Vasenev, J.J. Stoorvogel, V.G. Plyushchikov,
N.D. Ananyeva, K.V. Ivashchenko, O.N. Romzaykina, 2016.

REFERENCES

- [1] Alexandrovskaya, E.I. and A.L. Alexandrovskiy. 2000. History of the cultural layer in Moscow and accumulation of anthropogenic substances in it. *Catena* 41: 249—259.
- [2] Ananyeva N.D., E.A. Susyan, O.V. Chernova, and S. Wirth. 2008. Microbial respiration activities of soils from different climatic regions of European Russia. *European Journal of Soil Biology* 44: 147—157.

- [3] Anderson TH, Domsch KH (1986) Carbon links between microbial biomass and soil organic matter / In: F. Megusar, M. Gantar (Eds.) *Perspectives in Microbial Ecology*. Slovene Society for Microbiology, Ljubljana, 467—471.
- [4] Baldocchi, D., E. Falge, L. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C., Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, U.K.T Paw, K. Pilegaard, H.P Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson and S. Wofsy. 2001. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem — Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bulletin of American Meteorological Society* 82: 2415—2434.
- [5] Bekku, Y., H. Koizumi, T. Oikawa and H. Iwaki. 1997. Examination of four methods for measuring soil respiration. *Applied Soil Ecology* 5: 247—254.
- [6] Bispo, A., D. Cluzeau, R. Creamer, M. Dombos, U. Graefe, P.H Krogh, J.P. Sousa, G. Peres, M. Rutgers, A. Winding and J. Römbke. 2009. Indicators for monitoring soil biodiversity. *Integrated Environmental Assessment and Management* 5: 717—719.
- [7] Bloem, J. and Breure, A.M. (2003). Microbial indicators. In Markert, B.A., Breure, A.M., Zechmeister, H.G. (Eds.). *Bioindicators and biomonitors* (pp. 259—282). Oxford: Elsevier.
- [8] Bloem, J., A.J. Schouten., S.J. Sørensen, M. Rutgers, A. Van der Werf and A.M. Breure. 2006. Monitoring and evaluating soil quality. In J. Bloem, A. Benedetti and D.W. Hopkins, editors. *Microbiological Methods for Assessing Soil Quality*. CAB International. Wallingford. Oxfordshire. UK.
- [9] Bond-Lamberty, A. and A. Thomson 2010a. A global database of soil respiration data. *Biogeosciences* 7: 1915—1926.
- [10] Bond-Lamberty, A. and A. Thomson 2010b. Temperature-associated increases in the global soil respiration record. *Nature* 464: 579—582.
- [11] Borovikov, V. 2003. *Art of computer data analysis*. Piter. Saint-Petersburg.
- [12] Buyanovsky, G. A., G. H. Wagner and C. J. Gantzer. 1986. Soil respiration in a winter wheat ecosystem. *Soil Science Society of America Journal* 50: 338—344.
- [13] Carlyle, J.C. and U.B. Than. 1988. Abiotic controls of soil respiration beneath an eighteen-year old *Pinusradiata* stand in south-eastern Australia. *Journal of Ecology* 76: 654—662.
- [14] Chapin, III F.S., G.M. Woodwell, J.T. Randerson, E.B. Rastetter, G.M. Lovett, D.D. Baldocchi, D.A. Clark, M.E. Harmon, D.S. Schimel, R. Valentini, C. Wirth, J.D. Aber, J.J. Cole, M.L. Goulden, J.W. Harden, M. Heimann, R.W. Howarth, P.A. Matson, A.D. McGuire, J.M. Melillo, H.A. Mooney, J.C. Neff, R.A. Houghton, M.L. Pace, M.G. Ryan, S.W. Running, O.E. Sala, W.H. Schlesinger and E.D. Schulze, 2006. Reconciling Carbon-cycle Concepts, Terminology, and Methods. *Ecosystems* 9: 1041—1050.
- [15] Creamer, R.E., R.P.O. Schulte, D. Stone, A. Gal, P.H. Krogh, G.L. Papa, P.J. Murray, G. Peres, B. Foerster, M. Rutgers, J.P. Sousa and A. Winding. 2014. Measuring basal soil respiration across Europe: Do incubation temperature and incubation period matter? *Ecological Indicators* 36: 409—418.
- [16] Egorov, V.V., V.M. Fridland, E.N. Ivanova, N.I. Rosov (Eds.). 1977. *Classification and diagnostics of soils in USSR*. Kolos. Moscow.
- [17] FAO. 1988. *Soils map of the world: revised legend*. Food and Agriculture Organization of the United Nations, Rome.
- [18] Fridland, V.M. (ed.). 1988. *Soil Map of the Russian Soviet Federative Socialist Republic at scale 2.5 M*. All Union Academy of Agricultural Science, Government Administration on Geodesy and Cartography (GUGK). USSR. 16 sheets.
- [19] Gavrilenko, E.G., E.A. Susyan, N.D. Anan'eva and O.A. Makarov. 2011. Spatial Variability in the Carbon of Microbial Biomass and Microbial Respiration in Soils of the South of Moscow Oblast. *Eurasian Soil Science* 44: 1125—1138.

- [20] Gomes-Casanovas, N., R. Matamala, D.R. Cook and M.A. Gonzalez-Meler. 2012. Net ecosystem exchange modifies the relationship between the autotrophic and heterotrophic components of soil respiration with abiotic factors in prairie grasslands. *Global Change Biology* 18: 2532—2545.
- [21] Grimmond, C.S.B., T.S. King, F.D. Cropley, D.J. Nowak and C. Souch. 2002. Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago. *Environmental Pollution* 116: 243—54.
- [22] Hamilton, J.G., E.H. DeLucia, K. George, S.L. Naidu, A.C. Finzi and W.H. Schlesinger. 2002. Forest carbon balance under elevated CO₂. *Oecologia* 131: 250—260.
- [23] Harder, C., T. Ormsby and T. Balstrom. 2011. *Understanding GIS: An ArcGIS project workbook*. ESRI press.
- [24] Houghton, R.A. 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850—2000. *Tellus* 55B: 378—390.
- [25] Huang N., J.S. He and Z. Niu. 2013. Estimating the spatial pattern of soil respiration in Tibetan alpine grasslands using Landsat TM images and MODIS data. *Ecological Indicators* 26: 117—125.
- [26] Islam, K.R. and R R. Weil. 2000. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. *Agriculture, Ecosystems and Environment*. 79: 9—16.
- [27] Jo, H.K. and E.G. McPherson. 1995. Carbon Storage and Flux in Urban Residential Greenspace. *Journal of Environmental Management* 45: 109—133.
- [28] Kaye, J.P., R.L. McCulley and I.C. Burkez. 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. *Global Change Biology* 11: 575—587.
- [29] Kudryarov, V.N., G.A. Zavarzin, S.A. Blagodatsky, A.V. Borisov, P.U. Voronin, V.A. Demkin, T.S. Demkina, I.V. Evdokimov, D.G. Zamolodchikov, D.V. Karelin, A.S. Komarov, I.N. Kurganova, A.A. Larionova, O.V. Lopes de Gerenu, A.I. Utkin, O.G. Chertov. 2007. Carbon pools and fluxes in terrestrial ecosystems of Russia. Nauka. Moscow.
- [30] Kurganova, I.N. 2010. Emission and balance of carbon dioxide in terrestrial ecosystems of Russia. Doctoral thesis. Moscow State University. Moscow.
- [31] Kurganova, I.N., V.O. Lopes de Gerenyu, T.N. Myakshina, D.V. Sapronov and V.N. Kudryarov. 2011. CO₂ Emission from soils of various ecosystems of the southern taiga zone: data analysis of continuous 12 year monitoring. *Doklady Biological Sciences* 436: 56—58.
- [32] Kuzyakov, Y. and O. Gavrichkova. 2010. Review: Time lag between photosynthesis and carbon dioxide efflux from soil: A review of mechanisms and controls. *Glob Change Biology* 16: 3386—3406.
- [33] Larionova, A.A., I.N. Kurganova, V.O.L. de Gerenyou, B.N. Zolotareva, I.V. Yevdokimov and V.N. Kudryarov. 2010. Carbon dioxide emissions from agrogray soils under climate changes. *Eurasian Soil Science* 43: 168—176.
- [34] Lorenz, K. and E. Kandeler. 2005. Biochemical characterization of urban soil profiles from Stuttgart, Germany. *Soil Biology Biochemistry* 37: 1373—1385.
- [35] Lorenz, K. and R. Lal. 2009. Biogeochemical C and N cycles in urban soils. *Environment International*: 35, 1—8.
- [36] Minasny B., A.B. McBratney, B.P. Malone and I. Wheeler. 2013. Digital mapping of soil carbon. *Advances in Agronomy*. 118. 1—47.
- [37] Nakadai, T., H. Koizumi, Y. Usami, M. Satoh and T. Oikawa. 1993. Examination of the methods for measuring soil respiration in cultivated land: Effect of carbon dioxide concentration on soil respiration. *Ecological Research* 8: 65—71.
- [38] Naumov V.D. (Ed.). 2009. 145 years to forest experimental station of RSAU-MTAA. RSAU-MTAA. Moscow.
- [39] Nilsson, S., A. Shvidenko, V. Stolbovoi, M. Gluck, M. Jonas, M. Obersteiner. 2000. Full carbon account for Russia. Laxenburg.

- [40] Nortcliff, S. 2002. Standardization of soil quality attributes. *Agriculture, Ecosystems and Environment* 88: 161—168.
- [41] Pataki, D.E., R.J. Alig and A.S. Fung. 2006. Urban ecosystems and the North American carbon cycle. *Global Change Biology* 12: 2092—2102.
- [42] Pell, M., J. Stenström and U. Granhall. 2006. Soil Respiration. In: Bloem J, Hopkins DW, Benedetti A (Eds.), *Microbial Methods for Assessing Soil Quality*. CAB International, Wallingford, Oxfordshire, U.K.
- [43] Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.G. Boone, P.M. Groffman, E. Irwin, S.S. Kaushal, V. Marshall, B.P. McGrath, C.H. Nilon, R.V. Pouyat, K. Szlavecz, A. Troy and P. Warren. 2011. Urban ecological systems: scientific foundations and a decade of progress. *Journal of Environmental Management* 92: 331—362.
- [44] Pouyat, R.V., I.D. Yesilonis and D.J. Nowak, 2006. Carbon storage by urban soils in the United States. *Journal of Environmental Quality* 35: 1566—1575.
- [45] Raich, J.W. and A. Tufekcioglu. 2000. Vegetation and soil respiration: correlations and controls. *Biogeochemistry* 48: 71—90.
- [46] Russian Federation State Statistic Service (RFSSS). 2012. *Population of Russian Federation*. Moscow.
- [47] Savage, K.E. and E.A. Davidson. 2003. A comparison of manual and automated systems for soil CO₂ flux measurements: trade-offs between spatial and temporal resolution. *Journal of Experimental Botany* 54: 891—899.
- [48] Scalenghe, R. and F.A. Marsan. 2009. The anthropogenic sealing of soil in urban areas, *Landscape and urban planning* 90: 1—10.
- [49] Schulze, E.D. 2006. Biological control of the terrestrial carbon sink. *Biogeosciences* 2: 147—166.
- [50] Shishov L.L. and N.V. Voinovich (Eds.). 2002. *Soils of Moscow Region and Their Use*. Dokuchaev Soil Science Institute. Moscow.
- [51] Shishov, L.L., V.D. Tonkonogov, I.I. Lebedeva and M.I. Gerasimova. 2004. *Classification and Diagnostics of Russian Soils*. Dokuchaev Soil Science Institute, Moscow (in Russian).
- [52] Smagin, A.V. 2005. *Soil gas phase*. Moscow University. Moscow (in Russian).
- [53] Susyan, E.A., D.S. Rybyanets and N.D. Ananyeva. 2006. Microbial Activity in the Profiles of Gray Forest Soil and Chernozems. *Eurasian Soil Science* 39: 859—867.
- [54] Trumbore, S. 2006. Carbon respired by terrestrial ecosystems — recent progress and challenges. *Global Change Biology*, 12: 141—153.
- [55] Vasenev, V.I., N.D. Ananyeva and O.A. Makarov. 2012. Specific features of the ecological functioning of urban soils in Moscow and Moscow oblast. *Eurasian Soil Science* 45: 194—205.
- [56] Vasenev, V.I., N.D. Ananyeva and K.V. Ivachenko. 2013a. Influence of contaminants (oil products and heavy metals) on microbiological activity of urban constructed soils. *Russian Journal of Ecology* 6: 475—483.
- [57] Vasenev, V.I., J.J. Stoorvogel and I.I. Vasenev. 2013b. Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. *Catena*. 107: 96—102.
- [58] Vasenev, V.I., J.J. Stoorvogel, I.I. Vasenev and R. Valentini. 2014. How to map soil organic stocks in highly urbanized region? *Geoderma* 226—227: 103—115.
- [59] Wardle, D.A. 1992. A comparative assessment of factors which influence microbial biomass carbon and nitrogen level in soil. *Biological Review* 67: 312—358.
- [60] Wilson, K.B. and D.D. Baldocchi. 2000. Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. *Agricultural and Forest Meteorology* 100: 1—18
- [61] Winding, A., K. Hund-Rink and M. Rutgers. 2005. The use of microorganisms in eco-logical soil classification and assessment concepts. *Ecotoxicology and Environmental Safety* 62: 230—248.
- [62] Yuste, J.C., D.D. Baldocchi, A. Gershenson, A. Goldstein, L. Misson and S. Wong. 2007. Microbial soil respiration and its dependency on carbon inputs, soil temperature and moisture. *Global Change Biology* 13: 2018—2035.

DOI: 10.22363/2312-797X-2016-4-94-107

ИСПОЛЬЗОВАНИЕ БАЗАЛЬНОГО ДЫХАНИЯ ДЛЯ АПРОКСИМАЦИИ ПРОСТРАНСТВЕННОГО РАЗНООБРАЗИЯ ЭМИССИИ CO₂ ПОЧВАМИ МОСКОВСКОЙ ОБЛАСТИ

**В.И. Васенев¹, Е. Штурвогель², В.Г. Плющиков¹,
Н.Д. Ананьева³, К.В. Иващенко^{1,3}, О.Н. Ромзайкина¹**

²Российский университет дружбы народов
ул. Миклухо-Маклая, 8/2, Москва, Россия, 117198

²Группа изучения Географии Почв и Ландшафтов
Университет Вагенинген, 47, Вагенинген, Нидерланды 6700 AA

³Институт физико-химических и биологических проблем, РАН
Институтская ул., 2, Пуццоно, Московская область, Россия, 142290

Почвенное дыхание (ПД) — важный источник эмиссии CO₂ наземными экосистемами. Несмотря на большое внимание, уделяемое анализу ПД на различных пространственных уровнях, в глобальных исследованиях преобладает информация о природных экосистемах и практически не упоминаются городские экосистемы. Урбанизация — одна из основных тенденций изменения современного землепользования, важность которой, вероятно, возрастет в будущем. Городские почвы содержат значительные запасы углерода и являются очень неоднородными и динамичными системами. Информация о пространственной изменчивости дыхания городских почв очень ограничена, особенно для регионов с различными биоклиматическими условиями и высоким уровнем урбанизации. Методология прямых измерений ПД в полевых условиях ограничивает число наблюдений. В качестве альтернативного подхода к аппроксимации пространственной изменчивости ПД рассмотрено базальное дыхание (БД). Используются методы цифровой почвенной картографии (ЦПК), для картирования БД как «прокси» ПД на примере неоднородной и высокоурбанизированной Московской области. Были построены цифровые карты БД для разных видов землепользования и типов почв для верхних и подстилающих почвенных горизонтов. Средние показатели БД для городских территорий были ниже, чем в лесах и на лугах, однако было показано, что именно территории поселений оказали основной вклад в пространственное разнообразие БД в регионе. Для городов был также показан значительный вклад нижних горизонтов в общее БД, достигающий 30%, что значительно выше по сравнению с фоновыми почвами. Несмотря на высокую неопределенность абсолютных значений ПД в регионе невелика, выявленная закономерность распределения БД по видам землепользования и типам почв не вызывают сомнений.

Ключевые слова: городские почвы, функции почв, микробное дыхание, урбанизация, почвенное картографирование