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This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE)

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Thesis

submitted in fulfillment of the requirements for the degree of doctor

at Wageningen University

by the authority of the Rector Magnificus

Prof. Dr A.P.J. Mol,

in the presence of the

Thesis Committee appointed by the Academic Board

to be defended in public

on Tuesday 8 December 2015

at 4 p.m. in the Aula.

Viacheslav I. Vasenev
How does urbanization affect spatial variability and temporal dynamics of soil organic carbon in the Moscow region?
216 pages.

PhD thesis, Wageningen University, Wageningen, NL (2015)
With references, with summary in English

ISBN 978-94-6257-589-9

Table of Contents

1. GENERAL INTRODUCTION

1.1. Soil organic carbon as a key parameter of soil quality

The carbon cycle is one of the principle biogeochemical cycles and likely the most studied one. Carbon stocks in the atmosphere, the ocean and terrestrial ecosystems, and carbon fluxes between them play an important role in key processes, such as soil formation, biomass production and climate change. Carbon stocks and fluxes and their biogeochemical and anthropogenic drivers attract increasing attention of scientitists and policy makers. Several international projects (e.g. the Global Carbon Project, www.globalcarbonproject.org; and the Global Carbon Atlas, www.globalcarbonatlas.org) and intergovernmental initiatives, such as the Intergovernmental Panel on Climate Change (IPCC; www.ipcc.ch) provide global carbon assessments and forecasts. Monitoring networks, such as FLUXNET (www.fluxnet.ornl.gov), and data analysis centers, such as the Carbon Dioxide Information Analysis Center (www.cdiac.esd.ornl.gov) provide timely data on carbon stocks and fluxes for different ecosystems world-wide.

The largest pool of actively cycling carbon in terrestrial ecosystems can be found in soils, which accumulates about 1500-2000 Pg (10^{15} g) C (Swift, 2001; Janzen, 2004). These soil carbon stocks include biochemical substances of different origin (e.g. organic, inorganic and black carbon), chemical structure (e.g. carbohydrates, humic and fulvic acids, and aromatic and aliphatic compounds) and mobility (i.e. active, slow and passive; Coleman et al., 1997; Orlov, 1998; Swift, 2001). Fractioning soil organic carbon is critical to model local carbon turnover. However, in regional and global carbon assessments, where fractional data are limited and the heterogeneity of bioclimatic and soil conditions is large, more integral parameters, such as soil organic carbon (SOC) or soil organic matter (SOM), are used.

Historically, SOC and SOM values are widely accepted indicators of soil quality. For example, SOC depletion is used as a basic indicator of soil degradation (Nortcliff, 2002; Bastida et al., 2008). Many local surveys and farmers from all over the world report SOC and SOM content as a critical feature for soil fertility and agricultural quality (Ali, 2003; Barrios and Trejo, 2003; Mairura et al., 2007). Crop models, agroecological models and decision support systems also consider carbon content as an important driver for yield assessments (Rossiter, 1989; 1990; Vasenev and Bukreev, 1994; Albizua et al., 2015). The shift in recent decades from traditional agricultural attitudes of soil as a substrate for food production to its role in essential ecological processes and functions highlighted the importance of soil carbon stocks and fluxes (Bolin et al., 1979; Kovda & Rozanov, 1988). Carbon sequestration, for example, is an important process to mitigate climate change (IPCC, 2001; Lal, 2003; Janzen, 2004), whereas soil respiration is the largest biogeochemical carbon efflux into the atmosphere, contributing to climate change (Raich et al., 2002; Schulze, 2006). Soil microbial carbon indicates the soil's performance as a habitat for microorganisms. Soil microbial communities contribute to biodiversity and gene reservoirs (Andrews et al., 2004; Blum, 2005; Dobrovolsky and Nikitin, 2012). The relation between soil microbial carbon and microbial respiration, defines the microbial metabolic coefficient, which is widely accepted as a relevant indicator of the state of microbial soil communities and ecosystem disturbance (Anderson and Domsch, 1985; Dilly et al., 2003; Bastida et al., 2006).

Many studies to classify and assess soil functions acknowledge the role of SOC (e.g. BBodSchG, 1998; Karlen et al., 2003; Andrews et al., 2004; Blum, 2005; Dobrovolsky and Nikitin, 2012). Table 1.1 illustrates the major roles that SOC plays for different soil functions from different soil function's classifications used in the USA, Europe and Russia.

Table 1.1 Carbon-related soil functions in different classifications[1]

Blum (2005)	Nortcliff et al. (2002)	Ritz et al. (2009)	BBodSchG (1998)	Andrews et al. (2004)	Dobrovolsky et al. (2012)
• Biomass production • Participating in biogeochemical cycles, including gas exchange between soil and atmosphere • Source of raw materials	• Provision of physical, chemical and biological settings for living organisms • Supporting biological activity and diversity for plant growth • Filtering, buffering, degrading organic and inorganic substances	• Food and fibre production • Environmental interactions, including carbon retention • Supporting habitats and biodiversity	• Participation in water and nutrient cycles • Decomposition • Basis for life of people, plants, animals and soil organisms • Land for agriculture and sylviculture • An archive of natural and cultural history	• Nutrient cycling • Biodiversity and habitat • Resistance and resilience	• Influence on the gas content • Storage of nutrients • Habitat for terrestrial organisms • Source for minerals' and fossils' formation • Transformation and transfer of sun energy to the earth bowels • Storage of historical artifacts

[1] We used the original names of the functions, given by the authors of each classification.

Substantial differences in approaches to classify soil functions (in terms of definitions and labels of each function, their total number and the classification's major purpose) make the comparison in Table 1.1 difficult. For example, the European and American classifications propose six or seven functions, usually subdivided to ecological and non-ecological functions (Blum, 2005) or natural and beneficial-to-humans functions (BBodSchG, 1998) with special attention to soil–human interactions. In contrast, the Russian classification with 32 soil functions (Dobrovolsky et al., 2012) gives much more attention to the interaction between soils and landscapes (at the biogeocoenotic level) and soils and environments (at regional and global levels). Classifications of soil functions in the UK (Ritz et al., 2009) and Germany (BBodSchG, 1998) were mainly developed to support land-use planning, whereas the Russian (Dobrovolsky et al., 2012) and American (Andrews et al., 2004) classifications are more suited to conserve nature. Although all these approaches differ, they all consider SOC as an important parameter: up to two thirds of the soil functions are directly or indirectly related to SOC stocks.

The recently emerged concept of ecosystem services (ESs; MA 2003) expands analyzing environmental properties, processes and functions with human economic benefits (de Groot, 1992; Constanza et al., 1997). Although, soil services are considered part of ESs (Breure et al., 2012), SOC directly or indirectly affect many specific ESs, including soil fertility maintenance, food production and climate regulation (MA, 2003; TEEB, 2010).

Information on SOC stocks is widely used in regional and global assessments of soil functions and ecosystem services (Kurbatova et al., 2004; Dominati et al., 2010; Bouma et al., 2015). In this context, the spatial variability and temporal dynamics in SOC play an important role influencing the accuracy of these assessments. The spatial-temporal variability of SOC is influenced by both environmental and anthropogenic factors. Environmental factors, including relief, parent material, vegetation, soil and climate create the 'natural basis' for the carbon emission from and the carbon sequestration in ecosystems (Kudeyarov et al., 2007; Chapin et al., 2006). Anthropogenic influences result in substantial and usually rapid alterations in SOC stocks, mainly caused by land-use change (IPCC, 2005; 2013). Changes in the spatial variability and temporal dynamic of SOC stocks as a result to land-use is the main focus of this thesis.

1.2. The influence of land-use change on soil carbon

Land-use change (LUC) is a major anthropogenic factor that contributes to food production, influences the world's carbon balance and influences to climate change (Guo and Gifford, 2002; IPCC, 2001). International regulations under the Kyoto Protocol of the United Nation Framework Convention on Climate Change (www.unfccc.int/2860.php) obliged participating countries to assess and report soil carbon stocks for different biomes and land-use types, including cropland, pastures, forests and wetlands. Special attention is given to land-use change (e.g. afforestation, reforestation and deforestation) and management (e.g. forest management, agricultural technologies, grazing land management, re-vegetation; Chiti et al., 2010). Hence, several local, regional and global studies reflect on the impact of various LUC pathways on C stocks and fluxes all over the world and at different scale levels.

General global and regional assessments claim that forests, grasslands and natural pastures are likely carbon sinks, whereas croplands are important carbon sources (Nilsson et al., 2000; IPCC, 2005; Valentini et al., 2014). More detailed analyses reveal considerable heterogeneity on carbon stocks and fluxes within different land-use and land-cover classes. For example, soils are reported as the main carbon stocks in boreal forests, whereas in tropical forest most carbon is stored in vegetation biomass (Kudeyarov et al., 2007). Young spruce forest can be an active carbon sink, whereas old-grown forest ecosystems can become a carbon source (Olchev et al., 2013). Organic farming has a high potential for carbon sequestration (Ivanov et al., 2005), whereas intensively fertilized croplands are important carbon sources (Larionova et al., 2010).

The analysis, assessment and modelling of the impact of LUC on SOC stocks remains among the most cited topics in recent ecological publications (more than 2,000 papers in Scopus by July 2015). However, the attention paid to different LUC pathways is far from equal. Most studies focus on natural (forest/meadows) and agricultural ecosystems (e.g. Islam and Weil, 2000; Hamilton et al., 2002; Cruvinel et al., 2011; Fromin et al., 2012). So far, natural sites are much better covered by long-term empirical data, than man-changed sites (Valentini et al., 2000). Remarkable changes in carbon stocks and emissions are reported after deforestation (Dixon et al., 1994; Lal, 2004; Fuchs et al., 2015) and during the initial years after converting natural forests into grasslands and croplands (Ivanov et al., 2005; Galford et al., 2010). Substantial changes also occur when abandoned agricultural lands are recolonized by natural vegetation (Kurganova et al., 2003; Vuichard et al., 2008). Much less, however, is known about the effect of urbanization on soil carbon stocks and fluxes.

Although urban areas occupy less than 3% globally, their area increased four times between 1970 and 2000 (Seto, 2011) placing urbanization among the most important land-use change pathways. Regionally, urban areas can cover more than 10% of the area and make a substantial contribution to the spatial variability of soils and vegetation (Kurbatova et al., 2004). The role of urban areas gets even more important, considering that their environmental effect is spread far beyond their legal boundaries (Svirejeva-Hopkins, 2004; Grimm et al., 2008). Currently more than two-thirds of the projected nine billion people will live in cities by 2050 (UN, 2008; FAO, 2013). Urban areas are becoming the main place where human interacts with environment. This highlights the importance of urban environmental quality, including features and functions of urban soils (Abrahams, 2002). SOC was shown above as an important soil feature and soil carbon sequestration is recognized among the basic soil functions, however, our knowledge on urban SOC stocks is limited. Some local studies report a large potential of urban soils to store carbon (Jo and McPherson, 1995; Bandaranayke et al., 2003; Vasenev et al., 2012), whereas others show that carbon emissions from urban soils are comparable or even surpassing those in adjacent natural and agricultural ecosystems (Kaye et al., 2004; 2005; Raciti et al., 2012). The regional and global effects of urbanization on soil carbon remain underappreciated and poorly studied. Urban SOC is often ignored because i) approaches to measure and assess carbons stocks in urban soils are constrained by, for example, high spatial heterogeneity and disturbed soil layers (Schulp and Verburg, 2009), and ii) disagreements in terminology and methodology exist between different countries and research schools in defining and confining urban areas (Raciti et al., 2012). My thesis aims to address these methodological constrains and to provide novel insights on how to quantify the spatial-temporal variability of urban SOC in urban areas.

1.3. Urbanization: definitions, drivers and environmental consequences

Urbanization is a key trend within current land-use change (Pickett et al., 2011). Several approaches to define urban areas exist in science and politicy. Conventional approaches to define urban areas are based on census data and can be formal or functional. Formal approaches define an area as urban based on its total population and population density. However, thresholds for the population density to define urban areas vary between countries. For instance, the US Statistical Bureau defines an area urban if the population density exceeds 1000 people per square mile (approximately 386/km^2) and the total population surpasses fifty thousand (USCB, 2010). The population threshold for a town in the Russian Federation is 12,000 people (Denisov et al., 2008). The functional approach defines areas on the basis of economic activities rather than on population density. Historically, urban areas are opposed to rural areas. Thus the percentage of citizens involved in non-agricultural activities is a widely used indicator to define a city (Denisov et al., 2008; Berry, 2008). More recently, remote sensing data are used to define an area as 'urban' using proxy values like the percentage of impervious surface areas (Raciti et al., 2012), normalized difference vegetation index (NDVI) (Lu and Weng, 2004), vegetation index built-up index (Stathakis et al., 2012) or 'nighttime lights' data (Pandey et al., 2013; Zhou et al., 2014).

Both conventional and remote sensing approaches have their limitations. Formal approaches may exclude newly settled built-up areas and cottage villages due to their limited size. However, they are usual early signs of urban expansion (Pickett et al., 2011) and their exclusion results in an underestimation of urbanization. The actualization of official borders in data sets does often not keep up with the speed of urban sprawl. Distinguishing urban areas based on satellite imaginary is likely more accurate, but the more detailed separation between urban green zones (i.e. parks, court yards and lawns) and non-urban forests and meadows is not precise. However, urban and non-urban green spaces need to be separated, since urban areas include considerable green zones (Svirejeva-Hopkins et al., 2004; Milesi and Running., 2005) and biogeochemical processes in these urban parks and green lawns are artificially altered (Vasenev, 2011; Zircle et al., 2011; Prokof'eva et al., 2013). Methodological constrains in distinguishing between urban parks and natural green spaces results in defining 'urban areas' as synonym to 'build-up areas', which underestimates an environmental value of urban ecosystems, especially in terms of carbon stocks and fluxes. An explicit definition of urban areas should be agreed upon, when analyzing urban SOC stocks, since using inconsistent definitions can result in large differences in the predicted SOC stocks, as was shown by Raciti et al. (2012) for the Boston Metropolitan Statistics.

Within this thesis urban areas are generally defined as the areas located within legal settlement boundaries and exposed to different functional use (i.e. recreational, residential and industrial). However, the definition is specified for the purposes of individual studies, represented in the thesis chapters. At first I focus on the non-sealed areas located within legal settlement boundaries for the comparative analysis of local SOC stocks in urban and non-urban areas. In the regional assessment and mapping I consider both impervious (i.e. built-up zones, roads and commercial land) and open areas (e.g. green zones, parks and lawns) inside the city. Finally, when modelling urbanization in the Moscow Region, both sealed and open spaces within settlements are included, although the formal city boundaries are determined by satellite imagery. This means that a built-up area adjacent to the city is likely to be urbanized even if it is not part of the formal city boundaries.

Urbanization includes both the establishment of new settlements and the expansion of existing settlements. LUC models explain urban expansion with different physical, socio-economic and neighborhood factors. Physical factors (including bioclimatic and topographic parameters) indicate the suitability of a territory for urban expansion. When the effect of urbanization on SOC stocks is analyzed, these physical factors are critical as they influence the spatial distribution of SOC stocks (McBratney et al., 2003; Dobrovolsky and Urussevskaya, 2004; Lal, 2004). Socio-economic factors include primary, census-based socio-economic variables (e.g. population and GDP) and proximity to socio-economic centers and transport infrastructures (e.g. roads, railroads and waterways; Cheng and Masser, 2003; He et al., 2006; Batisani and Yarnal, 2009). Neighborhood factors are traditionally defined as the proportion of different land-use types in surrounding areas (Stoorvogel and Fresco, 1996; Verburg et al., 2002; Zhang et al., 2010). Many studies show that the likelihood of a location to get urbanized is much higher when it is surrounded by existing urban areas (e.g. Müller et al., 2010; Li et al., 2013). This is logical, considering that infrastructural, economic and social conditions are usually more favorable for expansion of existing settlements than for establishing new ones (Pickett et al., 2011). A proportion of urban land in the neighborhood is therefore among the most frequently used variables in urbanization models (Fang et al., 2005).

Allocation of the new urbanized areas is a traditional outcome of urbanization models. However, when analyzing environmental consequences of urbanization, one shall consider much broader areas of disturbance than actually occupied by settlements (Kasanko et al., 2006). Urbanization alters vegetation, soil and fluxes of substances and energy. An established urban ecosystem strongly differs from a natural or agricultural ecosystem when urbanization converts it to serve urban purposes. Urban ecosystems are characterized by the man-changed and artificial landscapes with considerable anthropogenicdisturbances (e.g. environmental pollution, soil sealing, waste disposal). Cities generally consume much more energy than they generally provide, resulting in intensive emissions of heat, air and water contaminants and greenhouse gases (Odum, 1985).

Numerous evidences of the unfavorable ecological state of urban environments accumulated by the beginning of 21st century. Together with the continued increase of the global urban populations, this motivated the development of novel concepts like ‘sustainable cities’. The concept of sustainability resulted in the design of , for example, ‘emission free’ cities (Pickett et al., 2008) and ‘climate adapted’ cities (Raciti et al., 2011) which highlight the capacity of urban ecosystems to support specific (‘natural’) functions and services such as carbon sequestration. Carbon sequestration is a key soil function, contributing to important ecosystem services, such as climate regulation and maintenance of soil fertility. Whether urban ecosystems can perform as carbon sinks or sources is critical to evaluate the environmental sustainability of the city. Urban soils can play an important, but still poorly understood, role in carbon sequestration and emission in urban ecosystems. Urban soils can become increasingly important components of carbon assessments and models with increasing urbanization. Understanding the role and behavior of urban soils in carbon stocks and fluxes is urgently needed (Pataki et al., 2011; Smagin, 2012; Vasenev et al., 2012).

1.4. Urban soil: a potential carbon stock or source?

A key component of urban ecosystems is the soil. The conditions in which urban soils are formed and function are very specific and their influence on carbon stocks and fluxes is diverse. Anthropogenic soil-forming factors dominate in an urban environment and urban soils experience anthropogenic pressures through, for example, the translocation of soil material for construction, greenery work, soil compaction, sealing and pollution. Indirectly, urban soils are affected by humans who alter traditional soil-forming factors, such as climate, relief, parent material, vegetation and succession (Stroganova et al., 1997; Dobrovolsky and Urussevskaya, 2004). Mean air temperature in densely urbanized areas is likely higher compared to natural conditions (Savva et al., 2010). This so-called ‘urban heat island’ effect (Oke, 1973) is explained by extra heat produced by transport and energy sectors, and by the lower albedo of sealed surfaces increasing absorption of solar radiation (George et al., 2007). This effect results in an increased temperature of urban soils (Smagin, 2005). This temperature increase in turn can cause additional microbiological activity and accelerates SOM mineralization and SOC depletion.

Moisture regimes of urban soils are also often influenced by soil sealing, ground water control and mixing and translocation of parent material (e.g. during construction activities). Changes in runoff and infiltration probably lead to periodic water logging of urban soils (Kurbatova et al., 2004; Pickett at al., 2011) and this increases methane emission (Kaye et al., 2004). Vegetative covers are severely altered or converted to artificial surface covers. Only few tree species are capable to cope with the urban pressure, like air and soil pollution (Calfapietra et al., 2015; Churkina et al., 2015). This limits species selection in urban greenery and results in lower levels of biodiversity. Most open urban areas are occupied by green lawns (Milesi and Running, 2005). Ornamental trees and shrubs, lawns and flower-beds require specific soil and moisture conditions and therefore receive specific, often intensive soil management and they are frequently fertilized and irrigated.

Direct anthropogenic impacts on urban soils can have even more serious consequences on SOC stocks and fluxes. Sealed soils are likely excluded from carbon-cycle dynamics due to excavation of the most fertile topsoil and the subsequent sealing that isolates and blocks deeper soil layers and thus inhibit major soil fluxes. However, some evidence (e.g. Smagin, 2005; Scalendhe et al., 2009) shows that soil sealing can raise CO_2 emissions from neighboring open spaces due to lateral transfer. Compaction is another usual anthropogenic effect on urban soils (Craul, 1992; Jim, 1998). This limits soil respiration, which is likely to be lower in compacted urban soils than in undisturbed soils. In addition, compaction hampers favorable conditions for roots and soil microorganisms (Whalley et al., 1995; Siczek and Frac, 2012). Contamination is probably the most studied anthropogenic influence on urban soils. However, the influence of soil contamination on SOC stocks is poorly known. For instance, contamination can both increase (Khan and Scullion, 2002; Blagodatskaya et al., 2006; Vasenev et al., 2013a) and reduce soil respiration (Castaldi et al., 2004; Barajas-Aceves, 2005; Nwashukwu and Pulford, 2011). What happens depends on the type contaminants and their concentration.

The specifics in the formation and functioning of urban soils and the heterogeneity of factors that potentially alter urban soils' capacity to store carbon, and influence carbon emissions, are poorly known. The question, for example, remains whether urban soils are a net carbon source or sink (Grimmond et al., 2002; Pataki et al., 2006). Its answer is even more difficult to give, considering the unique spatial variability of urban soils, and their artificial dynamics.

1.5. Understanding variability of urban soil carbon in space and time: reasons and methodological constrains

The spatial variability in SOC stocks of urban areas is driven by a combination of bioclimatic and urban-specific factors (Vasenev et al., 2014b). Urban soils exist and function in zonal climatic conditions. They keep some zonal features and can contain buried horizons of the initial natural or agricultural soils. As a result, SOC stocks in urban soils differ between various bioclimatic regions (Stroganova et al., 1997; Pouyat et al., 2006; Vasenev et al., 2013c). At the same time, urban areas are also very heterogeneous because of differences in uses, management histories and other anthropogenic influences and disturbances. Combinations of different functional zones (e.g. industrial, residential and recreational) and areas of historical development (e.g. historical core, central zone and suburbs) contribute to this high heterogeneity of urban areas. Different levels of soil sealing, pollution and compaction further generate a 'patchy' spatial distribution. Given the variability of soil forming and altering factors, urban SOC stocks are likely to vary also at short distances, even if the original soil conditions are very similar.

The analysis of spatial variability of urban SOC stocks is further complicated by the very specific soil profile distributions of urban soils (Beyer et al., 2001; Lorenz and Kandler, 2005). Urban soil profiles can have several peaks in SOC concentrations (Gerasimova et al., 2003) as a result of pedological (humus accumulation) and anthropogenic processes. The latter ones result in formation of a very specific urban soil's horizon – a so-called 'cultural layer'. Originating from archaeology (Avdusin, 1980; Alexandrovskiy et al., 1998) the concept of cultural layers is getting increasingly used in urban ecology due to its specific soil features, such as a high level of heavy metals' accumulation (Evdokimova, 1986) and non-typical soil microbiological communities (Marfenina et al., 2008). From the perspective of SOC stocks, these cultural layers, including wooden remains, coal and buried non-urban horizons (Prokofieva and Stroganova, 2004), can content up to 3 to 5% SOC (He and Zhang, 2009; Dolgikh and Alexandrovskiy, 2010). With the depth of the cultural layer varying from 10cm to several meters as a matter of settlement's history (Alexandrovskaya and Alexandrovskiy, 2000), SOC stocks in urban subsoil layers should not be ignored.

Temporal dynamics in SOC stocks largely depend on a range of soil abiotic and biotic parameters that determine the balance between carbon uptake (through photosynthesis) and carbon efflux by soil respiration (Carlyle and Than, 1988; Gomes-Casanovas et al., 2012). The heterogeneous urban environment obviously causes much spatial-temporal variability of urban soils' respiration. This variability likely depends on land-use structure (e.g. soil sealing, functional zoning and recreational load), soil chemical features (e.g. pH, SOM and nutrient content) and management practices (e.g. irrigation, fertilization and green-keeping). Temporal dynamics in soil respiration strongly correlates with diurnal and seasonal changes in soil temperature and moisture regimes (Rey et al., 2002; Kurganova et al., 2003; Larionova et al., 2010). To predict urbanization's effects on soil carbon stocks, a better understanding of this spatial-temporal variability of urban SOC stocks and the factors driving them is urgently needed.

1.6. Urban soils in the Moscow Region

Although carbon stocks and fluxes in urban soils recently attract increasing attention of researchers, the empirical data is still biased towards USA and EU countries compared to Russia. Several global reviews (e.g. Baldocchi et al., 2001; Bond-Lamberty and Thomson, 2010a) claim data gaps in SOC stocks and soil respiration for the country. Available studies for Russia focus on natural and agricultural landscapes and ignore urban ecosystems (e.g. Nilsson et al., 2002; Kudeyarov et al., 2007; Ananyeva et al., 2008; Kurganova, 2010).

Insight in SOC stocks and fluxes in the urban ecosystems is needed for a wide range of land-use and practical purposes, such as urban soil construction, management and the design of urban green infrastructure and land-use planning. The data gap also constrains implementing global carbon balance and climate models to the Russian regions, especially to highly urbanized ones.

The Moscow Region (54 to 56°N; 35 to 38°E) is the most urbanized region in Russia. Moscow city (56°N; 37°E) is located in the centre of the Moscow Region is the main Russian city and among the largest megapolises of the world. With a total population of over twenty million people, the Moscow Region with Moscow city include 14% of Russian population (Ilina, 2000; Argenbright, 2008). This population settled on less than 0.3% of the country territory, resulting in a remarkable population density of 434 citizens per km^2. Historically, the Moscow Region was the socio-economical and cultural center of Russia. Factories and plants (mainly chemical, machinery and constructing) launched in the region during the industrialization in the beginning of the 20^{th} century increased the economical potential of Moscow Region but resulted in serious environmental problems. After the soviet period, Moscow city continued to develop as a world tourist and business center attracting labor and educational migration and resulting in a very centralized structure of the region. Environmental and social consequences of this centralized structure included over-population, traffic congestion and substantial urbanization (Bashkatova, 2011; Vishnevsky, 2011; Argenbright, 2013). The effects of this urbanization on soil functions, including carbon sequestration are still poorly studied.

The effects of urbanization on carbon stocks and fluxes in the Moscow Region are complex due to the diverse bioclimatic conditions and a complex land-use structure. Three bioclimatic zones with different vegetation and soils are distinguished in the region: i) south-taiga with Eutric Podzoluvisols in the north and middle part; ii) mixed forests with Orthic Luvisols on the left bank of Oka river and iii) forest-steppes with Luvic Chernozems in the south (Shishov and Voitovich, 2002). Non-urban land-use includes forests (around 40% of the total extent of the region), croplands and grasslands (another 40%), meadows and natural pastures (approximately 10%). Urban areas occupy 10% of the region and continue to grow last decades. Urbanization mainly occurs on forest and cropland areas, resulting in considerable changes in vegetation and soil cover.

The urbanization in the region and its effects on soils attracted attention of soil scientists to urban soils of the region and first of all of Moscow city. Although some studies on Moscow soils were done before, the first relevant investigation of representative urban soil profiles in Moscow city were conducted in the 1990s (Stroganova and Agarkova, 1993; Stroganova and Prokofieva, 1995; Stroganova et al., 1997). These studies described the typical morphological, physical and chemical features of the urban soils and highlighted specifics of the soil forming factors in Moscow city. Further research focused on the classification and diagnostics of urban soils (Gerasimova et al., 2003; Prokofyeva and Stroganova, 2004; Prokofyeva et al., 2011). Special attention was given to the chemical and biological pollution of urban soils and to soil sanitary quality (Ladonina et al., 1999; Yakovlev and Makarov, 2006; Marfenina et al., 2011). Carbon stocks and fluxes in urban soils lacked attention and mainly referred to soil fertility assessment (Kurbatova et al., 2004). Although point data on SOC stocks and carbon emissions from Moscow urban soils are available (Smagin, 2005 & 2012; Prokhorov et al., 2012), it was never extrapolated for the full region. Thus, comparative analysis of SOC stocks, their spatial distribution and dynamics in urban and non-urban soils for different bioclimatic conditions and spatial analysis of SOC stocks and soil respiration in the Moscow region are still lacking. This data gap limits our understanding of the role of urban soils in the regional carbon balance and it does not allow predicting possible consequences of urbanization on soil functions, including carbon sequestration. Lack of data on spatial variability and dynamics of SOC in urban soils and the rapid urbanization occurring in the Moscow region motivated me to conduct this PhD research.

1.7. Objectives and research questions

A comprehensively study of the urbanization effect on SOC stocks in regional assessment is challenged by its spatial heteregeneity and modelling complexity. Ignoring urban soils in regional carbon assessments adds to the uncertainty of their results. My research aims to improve understanding of urbanization effect on SOC stocks by adapting an advanced spatial and temporal analysis of carbon stocks and fluxes to urban environments. The methodology is implemented for the Moscow Region, which showed substantial urbanization over the last decades.

This aim is consistently addressed by answering four research questions (RQs) for the Moscow Region:

RQ1 What are the impacts of soil type, land-use type, settlement age and depth on urban SOC stocks?

RQ2 How variable are SOC stocks in urban soils and does inclusion of urban soils improve the regional SOC stocks' assessments?

RQ3 How does urban soil respiration and its spatial variability differ compared to those in non-urban areas?

RQ4 What are the net effects of future urbanization on regional SOC stocks?

I address RQ1 by a comparative analysis of SOC stocks in urban, agricultural, forested and meadow ecosystems in the Moscow Region. A number of urban-specific factors, such as extent, history of settlements and functional zoning, are included into this analysis. SOC stocks are analyzed separately for the topsoil (0-10cm) and subsoil (10-150cm) to understand different factors driving SOC stocks in the top and underlying horizons (including the 'cultural layers'). The high spatial variability of urban and non-urban SOC across different management and bioclimatic conditions in the Moscow Region is addressed by RQ2. An extensive database of SOC stocks is collected in urban and non-urban sites of the Moscow Region and this provides a solid base to answer RQ2. Sampling design, digital soil mapping techniques and analysis of spatial variability were adapted to map urban SOC stocks and implemented for the Moscow Region.

Analyzing temporal dynamics of the regional urban SOC stocks is challenging due to methodological constrains, although a better understanding of SOC stocks' temporal changes is urgently needed. Addressing this issue by the comparison between the present SOC stocks with ones measured in the past is not possible due to high heterogeneity of the research area and limited data, available for research plots in the past. Therefore, the main focus is given to soil respiration as the main carbon efflux from soil to the atmosphere and consequently an important parameter to illustrate temporal dynamic of SOC stocks. Soil respiration is also variable in time and space and a reliable proxy for analyzing and mapping soil respiration at the regional scale is needed. This issue is addressed in RQ3 by applying a comparative analysis of soil respiration, its spatial variability and temporal dynamics in urban and non-urban areas. Both direct and indirect methods are implemented to measure spatial variability of soil respiration. At first, data on soil respiration measured *in situ* (a chamber approach with an infrared gas analyzer) and under standardized conditions (i.e. basal respiration) was compared for the test area in Moscow City to explore the potential of basal respiration to approximate the spatial distribution of the carbon efflux from soils. Afterwards basal respiration was used to map potential regional soil carbon emissions, based on the methodology we developed for SOC stocks' regional mapping in RQ2.

Finally, the resulted SOC stocks for different land-use types and their regional and local spatial variability were incorporated in a model to project the net effect of alternative urbanization scenarios on SOC stocks in the Moscow Region, addressing RQ4. At first, the factors, driving urbanization in the region for the period 1980-2014 were analyzed and incorporated in a logistic regression model. The model described probability of urbanization in the Moscow Region as a function of environmental, socio-economic and neighborhood factors. Several urbanization scenarios were analyzed with especial attention to the New Moscow Project, assuming rapid urbanization in the areas of more than 2500 km^2 in the next decades. For each of the scenarios the developed soil mapping technique was implemented to analyze changes in SOC as affected by predicted urbanization. This analysis provides essential information for the Russian and Moscovian decision makers that plan future urbanization and city development.

1.8. Outline of the thesis

The introduction (Chapter 1) and the synthesis of this thesis (Chapter 8) connect the different independent scientific papers and a book chapter incorporated in Chapters 2 to 7 (Figure 1.1). Chapter 2 reviews the scientific relevance and methodologies to analyze SOC stocks and fluxes in urban environments, with a special emphasis on the Moscow Region. Conventional and urban-specific factors that influence urban soil carbon and its variability in time and space are described. The chapter also summarizes different approaches to monitor and assess carbon stocks and fluxes under laboratory and field conditions and at the multiple scales. Distinct drivers behind this spatial-temporal variability of SOC stocks in urban areas and techniques to measure, quantify and model them are then implemented in the following chapters.

Chapter 3 highlights SOC stocks in urban soils in comparison to natural and agricultural areas in the Moscow Region. Based on the results of intensive soil sampling campaign for urban soils, SOC concentrations of urban and non-urban soils are determined over variety of bioclimatic and management conditions. Special attention is given to spatial variability in SOC concentrations between and within different settlements and functional zones and to the factors driving this variability.

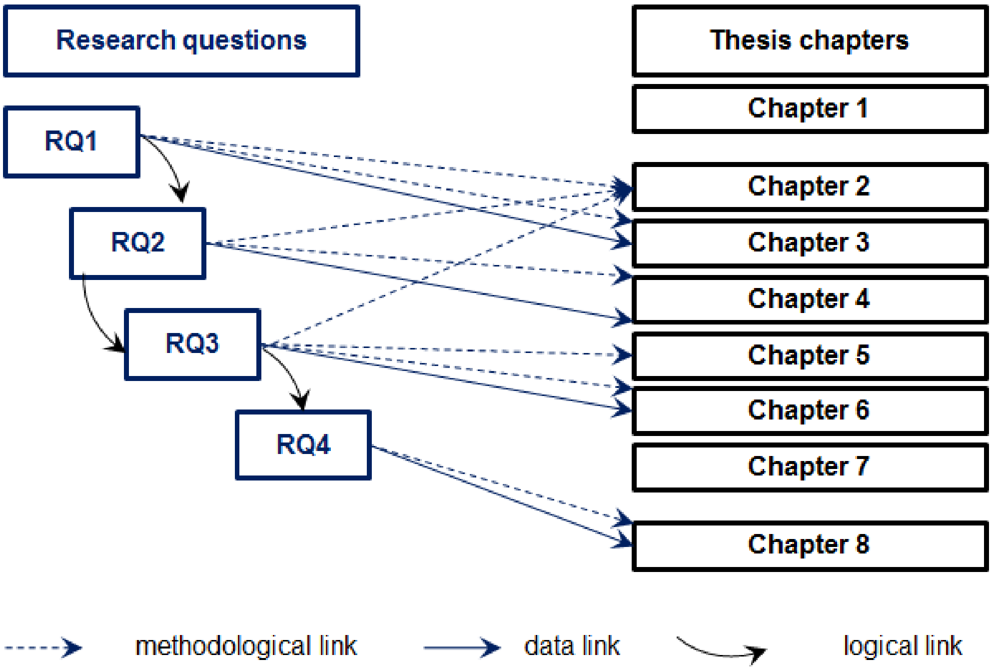


Figure 1.1 Schematic relations between research question and thesis chapters

Whereas Chapter 3 focuses on the open areas within settlements, Chapter 4's regional spatial analysis includes both impervious and non-sealed soils. This chapter tests and implements digital soil mapping techniques to analyze the actual spatial distribution of urban SOC stocks in the Moscow Region. Several general linear models, regressing different aspects of urban soils (from total ignorance to incorporating all urban-specific factors) are developed and implemented to obtain alternative maps of the regional SOC stocks. The spatial variances for different zonal soil types and land-use types are analyzed emphasizing the contribution of urban soils to regional variability of SOC stocks.

Chapters 5 and 6 analyze temporal dynamics and spatial variability of soil respiration as the main carbon efflux process. Different approaches of soil respiration analysis, such as *in situ* measurements and indirect basal respiration techniques, are reviewed in Chapter 5. Both methods are used to capture spatial variability in soil respiration at the test area in Moscow City, and their performance is compared. Basal respiration as a proxy value of soil respiration is further implemented to map potential soil carbon efflux in the Moscow Region and to describe factors, influencing their spatial variability (Chapter 6). Spatial analysis of regional SOC fluxes remains challenging due to high heterogeneity and temporal dynamics; however, different spatial trends in soil respiration are clearly shown for different land-use types in the Moscow Region with especial attention to urban areas.

Described specifics of urban soils' respiration and carbon stocks, and distinguished factors behind their spatial variability are finally implemented in a comprehensive scenario analysis in Chapter 7. Possible consequences of urbanization on SOC stocks in the Moscow Region are modelled. This analysis includes two distinct parts. First, urbanization in the Moscow Region in the coming decades is modelled as a function of environmental, social and neighboring factors. Three alternative scenarios are analyzed and this results in the three different urbanization maps. A predicted increase of urban areas combined with an allocation of converted forested, agricultural and meadow lands are determined. Finally, the methodology developed in Chapter 4 is implemented to map SOC stocks before and after urbanization and to quantify the net effect of urbanization on the regional SOC stocks.
The obtained results and the main findings are discussed and synthesized in Chapter 8. This chapter shows all the complexity and versatility of urbanization effects on SOC stocks and fluxes. Uncertainties, limitations and robustness of the various analyses and their conclusions (i.e. the answers to the RQs) are especially discussed and improvements or lessons learned for this pioneering research are examined. The results and conclusions are verified and interpreted from the perspective of urban soil's potential to support carbon sequestration and contribute to the concept of a sustainable city, which will get increasingly important with future urbanization.

2. URBAN SOIL CARBON: WHAT DO WE KNOW?

Abstract

Land-use change is the main anthropogenic factor influencing soil carbon stocks and fluxes. Urbanization is among the most important and rapid changes in land use. However, the influence of urbanization on soil carbon dynamics is still poorly understood. Given the differences between urban, agricultural, and natural soils, major differences in soil carbon stocks and fluxes can be expected. Carbon stocks can be similar or higher in urban soil compared to non-urban soils through the usage of organic substrates, turf-sand mixtures and fertilizers. At the same time, organic matter in these substrates may be unstable, leading to increased mineralization rates, which may be further accelerated through increased average temperatures in the urban ecosystems. Functional zoning coincides with the variation in soil cover and causes carbon stocks and fluxes to vary over short distances. As a result, we can expect considerable contribution of urban soil organic carbon stocks and dynamics to regional and global carbon balance. Various multi-scale methods are required to analyze, quantify and model local and regional urban soils' carbon stocks and fluxes. This chapter presents an overview of methods to quantify the spatial-temporal variability of carbon stocks and fluxes in urban soils. The methods range from local monitoring to regional spatial modelling and mapping. Local monitoring includes soil survey, chemical and microbiological analysis, and *in situ* measurements of soil respiration. Regional modelling focuses on digital soil mapping techniques to analyze spatial patterns of carbon stocks and fluxes in highly urbanized region and quantify urban areas' contribution to regional carbon balance. We will illustrate the various approaches for case studies in the Central European part of Russia.

Based on:

V.I. Vasenev, J.J. Stoorvogel, N.D. Ananyeva, K.V. Ivashchenko, D.A. Sarzhanov, A.S. Epikhina, I.I. Vasenev, R. Valentini. 2015. Quantifying spatial-temporal variability of carbon stocks and fluxes in urban soils: from local monitoring to regional modelling. Pages 185-222 In S.S. Muthu (Ed..) The Carbon Footprint Handbook. CRC Press. Boca Raton (FL), USA

2.1. Introduction

Carbon turnover is one of the major biogeochemical cycles on our planet. The carbon cycle determines the performance of many principle environmental functions and ecosystem services including soil fertility, biodiversity, and climate change (Kudeyarov et al., 2007; IPCC, 2013; FAO, 2013). The largest pool of actively cycling carbon in terrestrial ecosystems is found in the soil that contains about 1,500-2,000 Pg C in various forms (Swift, 2001; Janzen, 2004). Carbon sequestration is therefore a widely accepted soil function (Blum, 2005; MA, 2003). Soils are major carbon sinks, but they also have the potential to emit carbon to the atmosphere through carbon dioxide (CO_2) and methane (CH_4) effluxes (Houghton, 2003a; Chapin III et al., 2009; Levy et al., 2012). The storage of soil carbon but also effluxes are influenced by a wide range of different bioclimatic conditions and land-use.

In comparison to well known effects of deforestation, reforestation and land abandonment on the carbon cycle, the influence of urbanization on soil carbon is still poorly understood. Global and regional studies often neglected the role of urban soils in the carbon cycle (Schaldach and Alcamo, 2007, Schulp and Verburg, 2009), although some case studies claim considerable potential of urban soils to store and emit carbon (Kaye et al., 2005; Golubewski, 2006; Lorenz and Lal, 2009; Raciti et al., 2011). Given that globally urban areas cover 2-3% of the land and urbanization continues to take place at a rapid pace (Saier, 2007; Pickett et al., 2011), a better understanding of carbon stocks and fluxes in urban soils.

Urban soils experience a range of anthropogenic effects. Soil sealing, contamination, and translocation are very direct impacts on the soil system (Lorenz and Lal, 2009; Pickett at al., 2011) whereas changes in the soil-forming factors are indirect effects on the soil in the urbanized environment (Gerasimova et al., 2003). As a result of the anthropogenic changes, urban soils have very different characteristics like a high spatial heterogeneity, time dynamics, and profile distributions that often differ from ones in natural and agricultural ecosystems (Vasenev et al., 2013c). Urban ecosystems are very complex and heterogeneous (Vrscaj et al., 2008) and the soils present a very high spatial variability in soil organic carbon (SOC) (Pouyat et al., 2006; Lorenz and Lal, 2009; Vasenev et al., 2014b). Studies into the spatial heterogeneity of urban SOC are further complicated by the specific profile distribution, including a considerable carbon storage in the subsoil. The profile distributions can include buried horizons, pre-urban zonal soils, or, so-called, cultural layers formed by long-term residential activity (Beyer et al., 2001; Lorenz and Kandler, 2005; Dolgikh and Alexandrovskiy, 2010). The variability of carbon fluxes from urban soils is even higher, considering temporal dynamics caused mainly by seasonal and diurnal trends of soil temperature and water regime. Some local studies report surpass of urban soil's respiration compared to adjacent natural or agricultural areas (Kaye et al., 2005), however the mechanisms behind this tendency are still poorly understood.

High heterogeneity of urban areas and lack of legacy data on carbon stocks and fluxes from urban soils limits our knowledge of carbon balance in urban ecosystems. The considerable carbon stock in urban soils together with reports of high soil respiration leave the question whether the urban soil is a net source or sink of carbon unanswered (Grimmond et al., 2002; Pataki et al., 2006) resulting in increasing uncertainty in regional and global carbon assessments. Therefore, the analysis of the carbon balance in the urban environment requires specific attention. The current chapter focuses on the key theoretical aspects of urban soils' formation and functioning (Section 2.2), approaches to analyze urban soil carbon and its variability it time and space (Section 2.3), and two case studies, in which these approaches have been implemented (Section 2.4). The first case study is a comparative analysis of soil microbial activity parameter in various ecosystems and addresses the influence of anthropogenic disturbance on carbon stocks and fluxes at the local scale. The second case study shows the contribution of bioclimatic conditions and land-use to the spatial-temporal variability of carbon fluxes at the ecosystem level. The literature review, methodology synthesis, and case studies aim to provide a full picture of the important role urban soils play in the carbon cycle and to improve our understanding of carbon stocks and fluxes in urban soil and their temporal variability at different spatial scales.

2.2. Soil as a key player of carbon cycle

2.2.1. Basic terms and concepts

Soil plays a key role in the carbon balance and make a major contribution to carbon stocks and fluxes. Carbon accumulates in soils in different forms with different chemical features and mobility. SOC is the major stock in terrestrial ecosystems, surpassing estimates of atmospheric and biotic pools by a factor two or three (Schlesinger, 1995; Swift, 2001; Lal et al., 2004). Soil inorganic carbon (SIC) is mainly stored as carbonates and contributes considerably to soil carbon stocks in arid climate (Eswaran et al., 1993; Orlov et al., 1998; Dobrovolsky and Urussevskaya, 2004). In addition to more conventional SOC and SIC, soil black carbon (BC), resulting from pyrogenic processes and anthropogenic effects, receives increasing attention (Schmidt and Noack, 2000; Cheng et al, 2008). Compared to other forms of soil carbon, microbial biomass carbon (C_{mic}) contributes minimally to the total stocks with 1-5% of total soil carbon (Sparling, 1992; Dalal and Allen, 2008). However, C_{mic} is the most labile form and influences key processes behind carbon sequestration and emission (Ananyeva, 2003; Ananyeva et al., 2008; Kurganova, 2010). The accumulation of soil carbon depends on a range of soil chemical, physical and biological processes that are usually related to the soil type and bioclimatic conditions. Anthropogenic influences can contribute to the buildup of carbon stocks, but can also be a potential risk of carbon emission from soils (Smagin, 2005). The CO_2 emission from soils to the atmosphere through biogeochemical and physical processes is traditionally referred to as soil respiration (Rs) (Kudeyarov, 1996; Smagin, 2005). Soil respiration is one of the predominant terrestrial CO_2 fluxes and responsible for about 80 Pg/yr of carbon emission back to the atmosphere (Raich et al., 2002; Schulze, 2006). Soil respiration includes two major flux components: autotrophic respiration (AR) by root systems and root-associated organisms and heterotrophic respiration (HR) by free-leaving microorganisms in the soil (Chapin et al., 2006; Gomes-Casanovas et al., 2012). Although, the relative contribution by HR and AR varies between ecosystems (Hanson et al., 2000), HR usually dominates and contributes to 60-75% of total respiration. Both components of soil respiration are very variable in time and space (Trumbore, 2006). Soil respiration has been correlated to a range of abiotic (soil temperature and moisture) and biotic factors (vegetation type, plant productivity, microbiological community and soil features) (Davidson and Janssens, 2006; Bahn et al., 2010; Kuzyakov and Gavrichkova, 2010; Gomes-Casanovas et al., 2012). Temporal (diurnal and seasonal) dynamics in soil respiration usually correspond with changes in climatic conditions (Rey et al., 2002; Kurganova et al., 2003; Kudeyarov et al., 2007), whereas the spatial variability mainly comes from different biomes and land-use (Hamilton et al., 2002; Cruvinel et al., 2011; Fromin et al., 2012).

The second largest soil carbon efflux is coming from CH_4 emission, which results from combination of the two contrary processes: anaerobic decomposition of soil organic matter by methanogenic microorganisms (Levy et al., 2012) and methane oxidation by methanotrophic bacteria (Dalal and Allen, 2008). Net CH_4 efflux depends on bioclimatic and management conditions and soil can act both as methane source and sink. Globally, wetlands and agricultural lands contribute mostly to the CH_4 emissions (Le Mer and Roger, 2001; Smith et al., 2008), although high spatial heterogeneity occurs.

Land-use is widely assumed as the most important factor affecting the soil carbon balance and is incorporated in most of global and regional models of carbon stocks and fluxes (Post and Known, 2000; Komarov et al., 2003; Sitch, 2003). So far, research on the soil carbon balance focuses on natural and agricultural ecosystems (Guo and Gifford, 2002; IPCC, 2001, 2007, 2013), on the consequences of land-use change (e.g. reforestation, deforestation, agricultural intensification and land abandonment), and on carbon stocks and fluxes (Vuichard et al., 2008; Galford et al., 2010; Kurganova et al., 2014). However, little is known about the effect of urbanization on carbon stocks and balances.

2.2.2. Carbon stocks in urban soils

Carbon stocks of urban soils remain very poorly studied compared to those in natural and agricultural soils, c. Most of the global and regional carbon assessments ignored the contribution from urban soils (Jobbagy and Jackson, 2000; Lal, 2004; Stockmann et al., 2013). However, some local studies in USA, China, Germany and Russia found similar or even higher soil organic carbon concentrations and stocks in urban soils compared to adjacent natural and agricultural ones (Kaye et al., 2005; Pouyat et al., 2006; Zircle et al., 2011; Vasenev et al., 2013c). High carbon stocks in urban soils are given two alternative interpretations: 1) favorable conditions for carbon sequestration in urban soils, and 2) adding artificial substrates with high amount of carbon (mainly, turf, peat and organic composts). The first concept is indirectly approved by the high net primary productivity of urban trees, shrubs and grasses due to the dominating juvenile growing phase, high soil fertility, and prolonged vegetation period caused by the heat island effect (Jo and McPherson, 1995; Gregg, 2003; Nowak, 2006). For instance, field observations of chronosequences and modelling using CENTURY showed a potential carbon sequestration up to 20-30 t C/ha on golf courses in Denver (Qian and Follet, 2002; Bandaranayke et al., 2003). Contrarily, it can be argued that the urban SOC is mainly imported. The latter is supported by chemical analysis of urban soil carbon showing significantly higher concentrations of aromatic hydrocarbons and black carbon and artificial inclusions of plastic particles in urban soils (Beyer et al., 2001; Lorenz et al., 2006). Whether urban SOC is sequestered locally or imported varies depending on anthropogenic pressure and functional use (Mesheryakov et al., 2005). Soil carbon stocks, as a result of incoming and outgoing carbon fluxes, are rather sensitive to anthropogenic pressures and dynamic in time. This is especially true for urban soils, where the level of anthropogenic disturbance is high and factors behind temporal dynamic of soil carbon are specific.

2.2.3. Carbon fluxes from urban soils

Just as for stocks, carbon fluxes from urban soil are often ignored in regional and global assessments (Raich and Tufekcioglu, 2000; Hamilton et al., 2002; Houghton, 2003a; Kudeyarov et al., 2007). A general view on urban soils as being artificial, polluted and sealed is the main reason why carbon fluxes from urban soils are often neglected (Scalenghe and Marsan, 2009). This standpoint, however, is just a partial view of the overall picture. An actual percentage of the impervious areas varies in different parts of the city and functional zones and may differ from 7 to 90% with an average of 50% (Kurbanova et al., 2004; Vasenev et al., 2013b). Sport and ornamental green lawns occupy up to 40% of the non-sealed territory (Milesi and Running, 2005). Moreover, for partly impervious areas with less than 90% of an area sealed decrease of carbon fluxes from impervious surfaces corresponds to considerable rise in carbon emission from adjacent open spaces due to lateral migration of carbon fluxes beneath sealed surfaces (Smagin, 2005; Scalendhe and Marsan, 2009).

Local studies in Arizona and Baltimore (USA) (Koerner and Klopatek, 2002; Kaye et al., 2005), Shanghai and Nanjing (China) (Sun et al., 2009; Zhang el al., 2010) evidence considerable urban soils respiration, which was similar to or surpassing respiration in natural areas. The drivers behind the urban soils' respiration are still poorly understood. Some authors explain this by higher SOC contents reported for urban soils (Pouyat et al., 2003; Zircle et al., 2011), including artificial organic substrates (compost and sewage materials) added during soil reclaiming and greenery work (Lorenz and Lal, 2009; Beesley, 2012). Others link higher urban soil respiration rates to urban heat island effect (Davidson, 1998) and alteration of soil physical properties (Chen et al., 2013).

Owing to the variation in disturbances, often, alternative views can be found. Soil compaction likely causes a decrease in soil respiration due to unfavorable conditions for microbiota and plant roots (Prokofieva and Stroganova, 2004). The effect of soil contamination remains uncertain. It can result in an increase but also a reduction of soil respiration. Soil pollution with gasoline and oil products likely cause rapid increases in respiration (Nwashukwu and Pulford, 2011; Vasenev et al., 2013a). The effect of soil contamination with heavy metals on soil respiration depends on the contaminant type and its concentration and vary from slight increase to dramatic decrease in soil respiration (Khan and Scullion, 2002; Blagodatskaya et al., 2006; Castaldi et al., 2004; Barajas-Aceves, 2005).

2.3. Methodological aspects to quantify spatial-temporal varibility of carbon stocks and fluxes in urban soils

2.3.1. Carbon stocks

<u>Field sampling of urban soils: challenges and constrains</u>

Soil organic carbon is an important carbon stock. Therefore, the correct design of soil sampling campaigns is important. Urban conditions provide a number of specific features (Section 2.2) and contribute to high spatial heterogeneity of urban soil. These specific features need to be considered when developing sampling protocols. Administrative and organizational reasons hamper the accessibility of urban areas for soil sampling. Soil sealing is one of the key urban factors influencing soil carbons stocks and fluxes and contributing to their spatial variability within a city. Sealed soils are referred as Ekranozems or Ekranic Technosols (Rossiter, 2007). The contribution of Ekranic Technosols to carbon stocks and fluxes remains almost unknown. Sampling sealed soils is very labor consuming, besides it is difficult to get approval by local authorities. The few studies on Ekranic Technosols report a high variability of carbon stocks from almost zero to considerable amounts depending on the surface construction type (buildings, roads, walking pathways etc) (Vasenev et al., 2013b). Carbon storage in Ekranic Technosols may become an important issue in investigation of urban soils in the coming future, although so far the absolute majority of research excludes sealed soils. Therefore, in the following text we will refer to the unsealed areas while talking about the urban soils.

Functional zoning and history of the settlement are other important urban-specific factors, influencing spatial variability of urban soils. Functional zoning is the stratification of the city territory into zones with contrasting allowed and regulated land management. The zones also differ in the level of anthropogenic pressure. Urban areas can typically be subdivided into industrial, residential and recreational zones. Industrial areas refer to open spaces around factories and along highways. Residential zones include private and public courtyards. Recreational zones are parks and green zones within urban infrastructure. Areas can also be subdivided into historical zones which refer to different periods of city development and expansion. They include the historical core, and other zones reflecting settlement boundaries in different historical periods. For example, five historical zones dating from XI century up to now are distinguished in Moscow city (Kurbatova et al., 2004). Functional zoning puts more influence on the topsoil carbon through anthropogenic pressure and management practices, whereas historical zoning likely corresponds to differences in subsoil carbon due to thickness and chemical features of the cultural layers. Both functional and historical zoning should be considered in sampling design and a relevant sampling scheme should include at least one plot from each of the functional zones within each historical zone (Vasenev et al., 2013b). Since internal spatial variability within functional zones can be high a minimum of 3-5 sampling points is required at each location (Vasenev et al., 2013c). This stratified randomized sampling design is assumed as the most relevant to study urban soil carbon (Vasenev et al., 2014b).

Additional constrains occur during the sampling process. The traditional approach starts with a soil pit followed by a description of the soil horizons based, and collecting soils samples from the horizons is usually of a very limited use in cities. Digging a soil pit is traditionally accompanied with considerable disturbances of surfaces vegetation (including green lawns and ornamental species), which is hardly appropriate in majority of urban areas or allowed. By locating the profile pits on the few allowed points one deals with a convenience sample that lacks the basic advantages of the probability sample. Urban soils profile usually contains a lot of artificial inclusions: wooden remains, bricks and construction wastes, but also cables and pipelines. Digging soil pits (but also augering) can be limited for safety reasons. Finally, soil preparation of a soil pit is a very time and labor consuming approach to collect soil samples and thus is not relevant for the studies requiring for considerable amount of samples. For instance, at least 100-250 points are needed in digital soil mapping (DSM) technique, which can hardly be collected in an urban area for a reasonable time period by making soil pits.

All these limitations give soil augering as a more appropriate technique to sample urban soils. Obviously, soil augering also has some constrains, like mixed boundaries between horizons and slight compaction. These constrains are negligible for spatial analysis of carbon stocks although can be critical for some kinds of pedological analysis. Thus, the final decision on the sampling approach depends on the purpose and scale of the research.

Another issue to be decided is a sampling depth. Many global and regional analysis of soil carbon focus on the topsoil (Bui et al., 2009; Mishra et al., 2010; Martin et al., 2011), which is of limited relevance for urban soils, where considerable amount of carbon is stored in the subsoil. Exact depth can depend on the settlement history. Older settlements likely possess thicker cultural layers and thus deeper sampling is needed (Vasenev et al., 2013 b, c). In any case, at least 100-150cm is a recommended depth to study carbon stocks in urban soils.

Field analysis of urban soils includes an in situ description of the soil profile and soil sampling. When describing soil profile it is necessary to focus on the features, required to classify urban soil and used for further estimation of soil carbon stocks: depth of soil horizons, color, texture, structure, gravel content, soil inclusions (both natural and artificial ones) and different evidences of urbopedogenesis (Rossiter, 2007; Prokofyeva et al., 2011, 2013). Each sampling point is georeferenced for further spatial analysis and modelling. To deal with the extreme short distance variability composite sampling is preferred, in which various samples are taken from, for example, 2 m^2 square plot (corners and center) and pooled into a single composite sample. Composite samples can be taken from genetic soil horizons or based on depth layers. The first option is preferable to describe profile distribution of soil carbon; the second one is more often used for comparative analysis of carbon stocks. Soil microbiological features are very sensitive to depth, thus samples for measuring soil microbial carbon are taken only on the layer basis. Collected soil samples are sent to the laboratory for further analysis.

<u>Laboratory analysis of urban soil carbon</u>

Samples collected in field for soil chemical analysis are air-dryied, sieved and pulverized to prepare them for laboratory analysis (Vorobyova, 1998). Soil samples for microbiological analysis do not receive this treatment to avoid disturbance of soil microbiota (Creamer et al., 2014). Possible set of the laboratory techniques to analyze urban soil carbon includes general approaches to quantify total carbon content and more detailed measurements of the different fractions: soil organic carbon (SOC), water soluble organic C (WSOC), hot-water soluble organic C (HWSOC), readily oxidizable C (ROC) and microbial biomass C (MBC).

Chemical analysis

Total soil carbon can be measured by direct and indirect approaches. Direct approaches are based on measuring CO_2 from soil combustion (dry combustion) or oxidation by chromic and sulfur acids (wet combustion) (Vorobyova, 1998; Fedorets and Medvedeva, 2009). Direct measurements of total soil carbon are usually done using CN analyzer (dry combustion) or by Knop approach (wet combustion) (Vorobyova, 1998). Indirect approaches are based on quantification of oxygen, required for oxidation of soil organic matter. The examples of these indirect techniques include Turin's approach based on oxidation of soil organic matter with dichromate solution and Turin's approach with Nikitin's modification based on dichromate oxidation with following spectrophotometric end point detection (Vorobyova, 1998).

WSOC is measured by adding distilled water, shaking in a centrifuge to extract the water-soluble phase with further measuring of organic C concentrations in the extracts using an automated dry combustion. The HWSOC is determined with a modified method of Sparling et al. (1998) including a water bath (80 ^{0}C) for 16h before shaking in centrifuge. Soil ROC is determined following the method of Graeme et al. (1995) using $KMnO_4$. BC is quantified using the chemical oxidation (CO) method applied by Lim and Cachier. In brief, the method consists of six steps: (1) weigh out 3.0g of dried soil sample, sieved by 100 mesh sieve, (2) removal of carbonates (acid treatment with 3mol/L HCl for 24 h), (3) removal of silicates (acid treatment with15mL 10mol/L HF: 1mol/L HCl for 24 h) (4) removal of CaF_2 (acid treatment with 15 mL 10mol/L for 24 h) (5) removal of organic carbon (CO with 15 mL 0.1 mol/L $K_2Cr_2O_7$: 2 mol/L H_2SO_4, 55°C for 60 h) and (6) the residual carbon is defined as BC, quantified by dry combustion on CN analyzer.

Microbiological analysis

Soil MBC is considered as the most dynamic and labile component of soil organic carbon. The pool of MBC, its activity and composition are the key parameters in soil processes, studied intensively in various ecological scenarios (Wardle 1992; Zvyaginzev 1994; Anderson and Domsch 2010). The methods to determine MBC are subdivided into two main groups: direct microscopic and indirect (biochemical, physiological) methods. Direct methods are used to determine quantity and contents of microorganisms, whereas indirect methods are implemented to estimate their activity, for example, respiratory activity, after fumigation or adding substrate. The method of fluorescence microscopy makes it possible to determine the length of mycelium of fungi and actinomycetes, to quantify bacterial and fungal spores, and to measure the diameter of mycelium and fungal spores in soil suspension on a glass mount stained with calcofluor white (for eukaryotes) or acridine orange (for prokaryotes) (Kozhevin 1989; Polyanskaya et al., 1995). However, implementing direct microscopy method to estimate soil microbial biomass is complicated by high subjectivity of the observer (Stahl et al., 1995; Domsch et al., 1979), and, therefore, the relevance and repeatability of the obtained results is questionable. The results of biochemical approaches to determine microbial biomass are less subjective, than ones obtained by direct microscopy methods. The limitations of indirect methods are related to the measurement of one of biomass compounds (ATP, DNA, muramic or diaminopimelic acid), and with the amount of easily mineralized (fumigation method) or functionally active (normal method) cellular components. However, the biochemical methods allow determination of different components of microbial cells and metabolic products and thus expand opportunities for more accurate investigation of the soil microbial biomass and its activity.

Substrate-induced respiration (SIR) invented at the end of the 1970s by Anderson and Domsch (1978) is among the most widely used biochemical methods to quantify soil microbial biomass and MBC as its proxy. It is based on the rate of initial maximal respiration of microorganisms after soil enrichment with an easily oxidized and universally available substrate - glucose. It is important that the time incubation of soil enrichment by glucose should not be more than six hours to exclude the reproduction of soil microorganisms (Mirchink and Panikov 1985). The heterotrophic microorganisms oxidize and co-oxidize the glucose for 3-5 hours after its addition to the soil (Anderson and Domsch 1978; Ananyeva et al., 2008; 2011). The respiratory response for this time period (the initial maximal respiration is determined experimentally for each soil type) allows estimating a unit of MBC (from µl CO_2 to µg CO_2-C) by coefficient. This estimation is based on one of the main principles of microbiology, claiming that the respiratory response of microorganisms (the production of CO_2) is directly proportional to their biomass (Pirt, 1975). The SIR method supposes to follow the conditions first related to the amount of glucose applied to the soil, the temperature of the pre-incubation (before the application of glucose), and the incubation (after the application of glucose) of the soil samples. The CO_2 production in the soils mainly resulting from the activity of heterotrophic microorganisms is known to be related to the hydrothermal conditions. As the carbon content in the soil microbial biomass is determined using the SIR method the moisture of the soils should not be less than 60% of the total water holding capacity (optimal for microorganisms) and the incubation temperature is taken as 22°C (temperature of the upper soil horizons in summer in most of the European countries) (Anderson and Domsch 1978). Prior to the estimation of SIR all soil samples (0.3-0.5 kg) are moistened up to 50-60% water holding capacity and pre-incubated in aerated bags at 22°C for 7 days to avoid an excess CO_2 production after mixing, sieving and moistening of soil sample (Ciardi and Nannipieri 1990; Ananyeva et al., 2008; Creamer et al., 2014). The SIR measurements are performed at least in triplicate and results are expressed per dry weight of soil (105ºC, 8 h). To measure SIR soil samples (2 g) are placed in a vial (15 ml volume) and a glucose solution is added drop-wise (10 mg glucose g^{-1} soil, volume was 0.1 ml). The vial is kept tightly closed and the time course is recorded. The vial is incubated (3-5 h, 22°C) and an air sample is taken and injected into a gas chromatograph for measuring CO_2 production. SIR (µl CO_2 g^{-1} h^{-1}) is calculated according to:

$SIR = (CO_{2,soil} - CO_{2,standard}) \times V_{fl} \times 60 \times 1000 / m \times \Delta T \times V_{as} \times 1000$

In which $CO_{2,soil}$ is the CO_2 content in the gaseous medium in the flask with the soil (vol %), $CO_{2,standard}$ is the CO_2 content in the gas in the empty flask (without soil) (vol %), V_{fl} is the volume of air in the flask with the soil (ml); m is the mass of the dry soil (g); ΔT is the time from the moment of closing the flask to take an air sample (min); V_{as} is the volume of the air sample introduced into the chromatograph (ml).

MBC is estimated based on the SIR results following:

$C_{mic} = SIR \times 40.04 + 0.37$ (Anderson and Domsch 1978).

There are different alternative views on the value of the coefficient to estimate microbial carbon from the respiration value. Possible values given in literature vary from 30 (Kaiser et al., 1992) to 50 (Sparling et al., 1990). However, the coefficient of 40.04 recommended by the original authors and confirmed by further research (West 1986; Martens 1987; Wardle and Parkinson, 1991) remains the most commonly used so far. The SIR method has the following advantages: sustainable quantitative determination of soil microbial biomass carbon, rapidity, high reproducibility, sensitivity and lower labor costs compared with other methods (e.g. direct microscopy of soil suspension and fumigation-extraction method) that allows for a large number of measurements (Anderson and Domsch 1978; Ananyeva et al., 2008). The method provides results with a relative error of less than 5% and takes into account only the active microbial biomass (Beare et al., 1990; Hassink, 1993; Wardle and Ghani, 1995). However, the SIR method also has some limitations. It is not appropriate for strong acidic (pH≤2.5) and alkaline (≥8.0) soils (Beck et al., 1997). Unlike practiced in Russian studies determining the microbial biomass by direct microscopic counts of microbial cells (number of bacteria, spores of fungi; lengths of fungal and actinomycetal mycelia) with subsequent consideration of their biovolumes and density, the SIR method allows determining of various additional physiological and metabolic parameters of the soil microbial community (Anderson, 1994).

Quantifying, modelling and mapping carbon stocks in urban areas

Most of the carbon surveys focus on two kinds of carbon stocks: total amount of carbon stored in the area of interest and specific amount of carbon per unit of area. The specific carbon stocks is urban soils are estimated following:

$SOC_{sp} = (SOC \times d \times K \times BD) / 10$

where SOC_{sp} is the specific soil organic carbon stock per area unit (kg/ m^2), SOC is the soil organic carbon content (%), d is the depth of the layer (cm), BD is the soil bulk density (g/cm^3) and K is the correction coefficient for, for example, rock material and artificial inclusions.

Total soil organic carbon is calculated based on extrapolation of SOC_{sp} for a single unit of study area (polygon or grid depending on the data type). In order to exclude sealed soils a correction coefficient for the percentage of open (non-impervious) area is introduced:

$SOC_t = SOC_{sp} \times S \times P_{oa} \times 10^3$

where SOC_t is total soil organic carbon stock (Tg), P_{oa} is the percentage of the open (non-impervious) area, and S is the area extent (km^2).

High heterogeneity of urban soil results in considerable spatial variability of their carbon stocks. Capturing this variability requires mapping and spatial modelling approaches considering specific condition of urban environment dealing with functional zoning, and the age and size of the settlements. Conventional soil surveys (Turin, 1959; Gavriluk, 1963; Fridland, 1972; Soil Survey Staff, 1999), presenting soil properties as qualitative data in the form of discrete maps, are of very limited use in urban environment due to constrains behind intensive sampling, described in 2.3.1.1.and high costs. Alternatively, recently developed DSM (McBratney et al., 2000; 2003) based on the modelling soil carbon stocks in new locations implementing obtained statistical relations between existing data on SOC stocks for a limited number of locations and auxiliary data available for the whole area of interest is an opportunity. However, both the sampling design and modelling set-up should be adapted to the specifics of urban environment (see Chapter 4 for more details).

2.3.2. Carbon fluxes

Urban soils can be a potential source of carbon through soil respiration (Kaye et al., 2004). Spatial- temporal variability of urban soil respiration is high and approaches to study this variability are needed. Conventional technique to determine sol carbon fluxes is based on direct field methods, where soil carbon effluxes are measured *in situ*, and indirect methods, where carbon fluxes are predicted based on auxiliary information or where they are measured under standardized conditions.

In situ measurement of soil carbon efflux

Direct methods include conventional alkali absorption techniques (Buyanovsky et al., 1986) and different chamber approaches (Nakadai et al., 1993; Bekku et al., 1997; Savage and Davidson, 2002). Currently used sampling and measuring procedures differ for CH_4 and CO_2 fluxes. The CH_4 flux is typically measured by a chamber approach. At least 4 hours before starting the measurements (to avoid disturbance), collars are mounted on the soil surface. Cylindrical chambers are placed on the top of collars and fixed by clips. The chamber is produced from chemically neutral material. A pressurized valve in the top of the chamber is used for gas sampling by a laboratory syringe. The chamber contains a temperature probe to control inside climatic conditions and a fan to mixture the air inside. The carbon flux is derived from rising or decreasing CH_4 concentrations inside the chamber. Gas samples are taken at least three times at, for example, 0, 30 and 60 minutes after starting the experiment and placed into 10-15 ml gas vials with airproof lids. CH_4 concentrations in the vials are measured using gas chromatography. The trend in CH_4 concentrations are approximated by linear or non-linear regression and the flux is estimated based on the ideal gas law, since the volume of the chamber and the extent of the analyzed soils surface are given (Smagin, 2005). In situ measurement of soil respiration (CO_2 efflux) can be conducted similarly to CH_4 although the methodology needs to be adapted given the higher effluxes of CO_2 from the soil compared to the CH_4 effluxes. Currently more advanced approaches using an infra-red gas analyzers are implemented to measure soil respiration in situ. Such gas analyzer provides measurements of CO_2 concentrations with a frequency up to 1 Hz or even higher and thus give much more accurate picture of the CO_2 flux.

Contribution of microbial and root respiration to soil CO_2 efflux is an important biogeochemical information. Methods to distinguish between SOC-derived and root-derived respiration are available both in laboratory and field conditions. The most frequently used are ones based on isotopic approaches (Pataki et al., 2003; Taneva and Gonzalez-Meller, 2011), trenching and field segregation (Leake et al., 2004; Gavrichkova et al., 2010). Implementation of these approaches and comparison of the results for forest and crop ecosystems was reviewed by Hanson et al. (2000). Each of the techniques has its advantages and disadvantages. Isotopic approaches provide the most precise results. However, the measurements are expensive and the amount of observation is typically limited. Field segregation provides a more general approach to quantify soil respiration *in situ*. It is based on the partitioning of soil respiration components by measuring two parallel plots, one of which is preliminary cleaned from existing roots and artificially isolated from intergrowth of outside roots (Leake et al., 2004; Gavrichkova et al., 2010). This approach is relatively cheap and simple and allows for a larger number of sampling points to, for example, consider spatial variability. However, soil disturbance during the experimental set-up requires for a long period before starting measuring to reestablish an equilibrium state (Hanson et al., 2000; Moyano et al., 2008). For all the approaches in which soil carbon fluxes are measured, the measurements usually include parallel monitoring of soil temperature and soil moisture as the key abiotic drivers of soil respiration.

<u>Indirect measurements of carbon fluxes</u>

Indirect methods relate carbon fluxes to proxy variables obtained, for example, based on remote sensing (Guo et al., 2011; Huang et al., 2013) or measurements of soil microbiological activity under standardized conditions. Deriving carbon emission from remote sensing considerably expands the study area. It is therefore widely used for global analysis. The limitation of the methodology is that the remote sensing image lacks a direct linkage to soil processes. Alternatively, spatial-temporal variability of soil respiration can be analyzed through a relatively easily measured proxy variable, referring to soil microbiological activity measured in standardized conditions. The rate of microbial (basal) respiration is one of the relevant proxies. The basal respiration is the respiration of soil without plant roots and is therefore associated to the soil microbial activity. The basal soil respiration is often referred to as “microbial respiration” of the soil, as opposed to the “root respiration”. Pre-incubation procedure for soil basal respiration measurement is similar to one described above for SIR. Basal respiration (BR) is determined by the CO_2 evolution rate from the soil incubated for 24 h at 22 °C as described for SIR. However, water (0.1 ml g^{-1} soil) is added to the soil samples instead of the glucose solution during SIR measurements. The BR is expressed in µg CO_2-C g^{-1} soil h^{-1}. 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 (Winding et al., 2005; Bispo et al., 2009). Experimentally obtained values of MBC and its basal respiration allow for the calculation of the “integrated” indicators of soil microbial community functioning:

the microbial metabolic quotient or qCO_2 (in µg CO_2-C mg^{-1} MBC h^{-1}) is the ratio BR/MBC - a specific respiration activity of soil microbial biomass. The qCO_2 value characterizes the sustainability of soil microbial community to anthropogenic influences (Ananyeva 2003);
the C_{mic}/C_{org} ratio (in %) is an additional parameter of soil quality (Anderson and Domsch, 1986), describing what part of total organic stocks is available for microbial consumption.
The qCO_2 is an informative indicator of the ecophysiological status of soil microorganisms. High qCO_2 values in disturbed soils indicate high energy losses and carbon consumption in the turnover of nutrients (Insam and Haselwandter 1989; Anderson and Domsch 1990). The MBC/SOC ratio is an indication of organic carbon availability (Anderson and Domsch 1986; Insam and Domsch 1988) and high values indicate the binding of organic matter in soil microbial biomass (Anderson and Domsch 1989). Changes in MBC/SOC reflect inputs of organic matter, conversion to microbial carbon, decomposition of carbon, and formation of organic carbon and mineral complexes in the soils (Wang et al., 2011). Therefore, these integral parameters allow getting additional information about the functioning of the soil microbial community under anthropogenic pressure.

2.4. Case studies

2.4.1. Introduction

Urbanization influences soil carbon stocks and fluxes in different aspects and at multiple scales. Alteration of the conditions and functioning of soil microbiological community results in changes in microbial biomass carbon stocks and microbial CO_2 production. Changes in temperature and moisture regime and physical disturbances affect temporal dynamics of soil respiration. Soil sealing and functioning zoning contribute to the spatial patterns of soil carbon stocks. Variability in space and time caused by different bioclimatic conditions, management practices and seasonal trends increases complexity of carbon stocks and fluxes in urban soils. The methodologies described in section 2.3 are implemented in two case studies in the Moscow and Kursk regions in Central Russia to illustrate how they capture this spatial-temporal variability. The choice of the relevant technique depends on the scale of analysis, research area and specific goals.
The first case study focuses on the microbial component of the carbon balance and analyzes the influence of land-use and bioclimatic conditions on the functioning of soil microbial community (Ivashchenko et al., 2014). Microbial biomass, microbial (basal) respiration and

structure of microbial community, represented through contribution of fungi and bacteria to total substrate-induced respiration, were measured in natural, arable and urban ecosystems within four administrative districts of the Moscow Region, differing in soil and bioclimatic conditions. An analysis of these soil microbiological activity parameters and the integral indexes qCO_2 and MBC/SOC illustrates the specifics of urban soils' capability to store and emit microbial carbon in a range of functional and bioclimatic zones. Considering that the major soil CO_2 efflux is coming from soil microbes, the case study contributes to understanding and quantification of the potential carbon emission from urban soils.

In contrast to the potential CO_2 emissions estimated based on the laboratory measurements in standard conditions, actual soil respiration measured *in situ* strongly depends on temperature and moisture parameters and thus varies between ecosystem, bioclimatic conditions and over the season. The second case study compares soil respiration from industrial, residential and recreational zones and reference urban forests in two settlements with different bioclimatic conditions: Moscow city located in south-taiga zone and Kursk city representing forest-steppe zone (Sarzhanov et al., 2015). Parallel observations of *in situ* soil respiration taken in June-November 2013 followed by measurement of air temperature, soil temperature and moisture provide an insight into the patterns of seasonal dynamics of soil CO_2 emissions and factors influencing it. Similar trends described for urban areas in different bioclimatic zones represents predominant influence of anthropogenic factor on soil respiration in urban environment over the bioclimatic conditions.

The combined influence of bioclimatic and urban-specific factors on the spatial variability of carbon stocks and fluxes is the most evident when modelling and mapping them regionally. Spatial patterns in soil organic carbon and basal respiration distribution over the Moscow Region, mapped using DSM technique, are described below in Chapters 4 and 6.

2.4.2. Spatial variability of urban soils' microbial carbon and respiration in contrasting bioclimatic and functional zones of Moscow Region

Introduction

The soil microbial community is the key driver behind soil functions (Martens, 1995; Anderson and Domsch, 2010) and plays a major role in the soil-atmosphere gas (CO_2 production) exchange (Conrad, 1996; Svirejeva-Hopkins et al., 2004; Zavarzin and Kudeyarov, 2006) and nutrient cycles. It is very sensitive to various anthropogenic impacts (Ananyeva, 2003; Colloff et al., 2008; Macdonald et al., 2009). Soil microbial community is very variable in space due to differences in the contents of organic matter and nutrients, pH, vegetation and land-use (Yan et al., 2003; Grinand et. al. 2008; Gavrilenko et al., 2011). So far major comparative studies of soil microbiological parameters are carried out within ecosystems, landscapes, and catenas. Research of microbiological properties of a specific area (e.g. at the regional or district level) in the context of the “spatial-horizontal” gradient of ecosystems, including urban ecosystems, are still very rare.

The contribution of the soil microbial community to formation of carbon fluxes and stocks in urban ecosystems at the regional and global level is poorly known (Lorenz and Lal, 2009; Bond-Lamberty and Thomson , 2010b). The urban environment influences the functioning of the soils’ microbial community, which in turn affects the respiration activity, structure, and diversity of the community (Kaye et al., 2005; Macdonald et al., 2009; Lysak, 2013). This case study focused on the soil microbial component and its respiration activity (CO_2 formation) of urban soils for four administrative districts of Moscow Region in comparison with natural (forest, meadow) and agroecosystems. The study addressed two main research questions: (1) Is the functioning of the soil microbial community deteriorated under the urban transformation? (2) Is an urban soil a potential source of atmospheric carbon dioxide?

Materials and methods

Soils of natural (forest, meadow) and anthropogenic transformed (arable, city) ecosystems of north-east and south-west of Moscow Region (Sergiev Posad, Shatura, Serpukhov, and Serebryanye Prudy districts (54°37´-56°26´N; 37°30´- 39°39´E), located in different bioclimatic zones of the region were studied (Figure 2.1). Annual average air temperature for the region is around 4°C and annual precipitation amounts up to 570-700mm. Eutric Podzoluvisols prevail in Sergiev Posad district; Gleyic Podzoluvisols, Fibric Histosols and Eutric Luvisols are predominant in Shatura district; Eutric Podzoluvisols and Orthic Luvisols dominates in Serpukhov district; and Luvic Chernozems prevails in Serebryanye Prudy district. Natural (forest, meadow) and anthropogenic transformed (arable, urban) ecosystems were selected in each district. Recreational, residential and industrial zones in urban areas were differentiated. Three to five sampling points were selected randomly in each observed ecosystem and functional zone of a district. In each of the 104 observation points a composite topsoil (0-10cm) sample was taken from a 2×2m plot (corners and centre). Soil samples were stored under field- moisture condition with air exchange under cooled conditions (8-10°C) for no more than 4 weeks before the analysis.

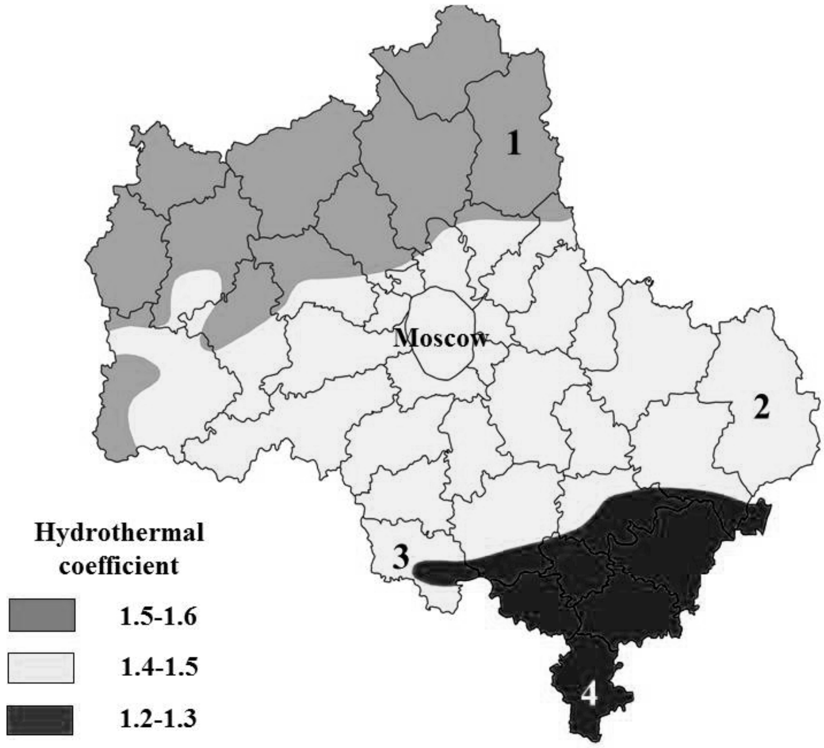


Figure 2.1 Bioclimatic zones of Moscow region. Districts: (1) Sergiev Posad; (2) Shatura; (3) Serpukhov; (4) Serebryanye Prudy

BC and microbial respiration (MR) were analyzed by substrate-induced respiration (SIR) and basal respiration (BR) approaches respectively (Anderson and Domsch, 1978; Ananyeva et al., 2011). Microbial metabolic quotient, qCO2 and MBC/SOC ratio were estimated (see section 2.3 for the detailed methodology). The contribution of fungi and bacteria to the total SIR of the soil was determined by the selective inhibition (SI) technique with antibiotics, and their ratio was calculated (Semenov et al., 2013).

Results

High spatial variability of MBC was found in the study areas and MBC variance in urban ecosystems was generally higher than in arable and natural ecosystems (Figure 2.2). Average MBC in forest and meadow soils (408-729 $\mu g\ C\ g^{-1}$) was 1.4-3.2 times higher than in arable ecosystems. MBC values within the urban areas were also heterogeneous with the lowest values obtained for industrial zone, which was were 1.7-2.7 times less compared to recreational and residential one.

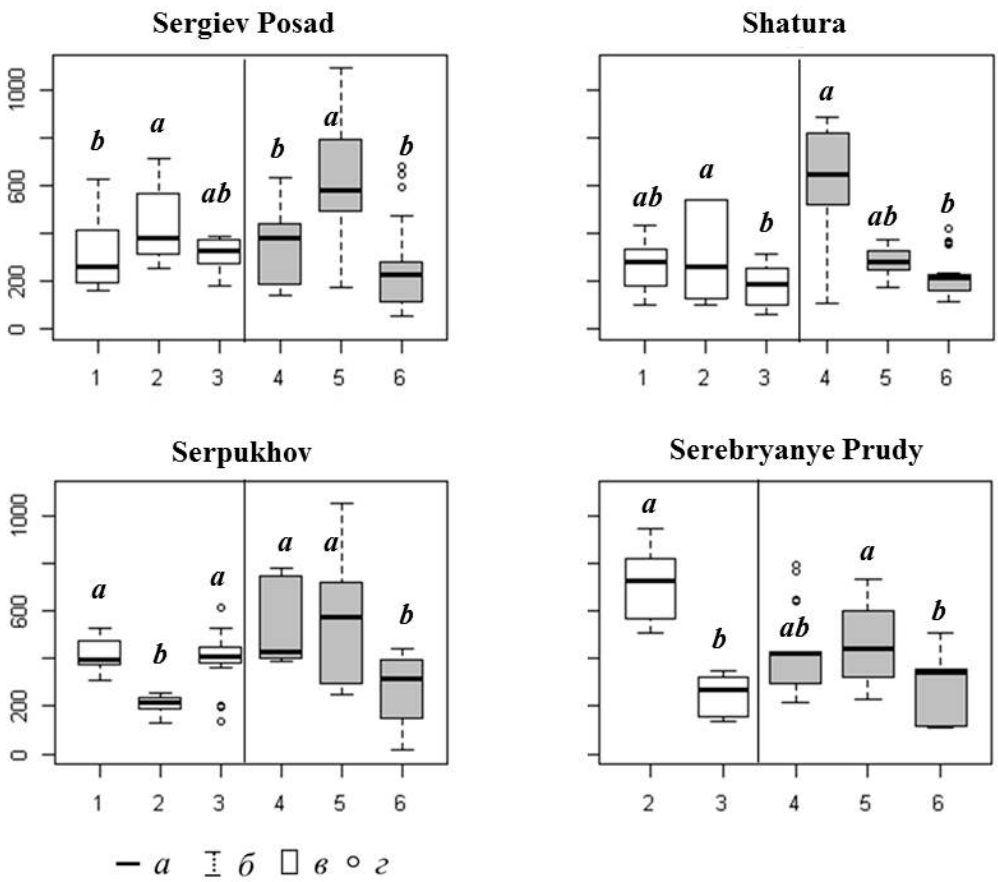


Figure 2.2 Distribution of microbial biomass carbon in the soils (0–10cm layer, μg C g^{-1}) in different ecosystems of Moscow region. Here and below, the designations are as follows: (*1*) forest; (*2*) meadow; (*3*) arable; (*4*) recreational zone; (*5*) residential zone; (*6*) industrial zone. The statistical characterization of the values is as follows: (*a*) median; (*b*) min–max; (*c*) 25–75%; (*d*) outliers. The values with different letters differ significantly (p ≤0.05) within each district and its functional zones separately

The similar trend was shown for basal (microbial) respiration of the studied soils with the lowest in urban industrial areas 0.13 and the highest – in forest ecosystems (0.13 and 3.08 μg CO_2-C g^{-1} h^{-1} correspondingly) (Table 2.1). Topsoil (0-10cm) MBC and MR in observed ecosystems were respectively 69-83% and 75-85 from the total profile values (Table 2.2).

Table 2.1 Basal respiration (μg CO_2-C g^{-1} h^{-1}) in the soils (0-10cm) of different ecosystems and functional zones in Moscow region

Ecosystem / zone	District (number of sites)			
	Sergiev Posad (28)	Shatura (30)	Serpukhov (24)	Serebryanye Prudy (22)
Forest	0.85-3.08 / 1.61 *a*	0.63-1.44 / 0.95 *a*	0.76-1.42 / 1.10 *a*	N/A
Meadow	0.57-1.97 / 1.17 *a*	0.56-5.41 / 1.92 *a*	0.30-0.45 / 0.37 *b*	0.40-1.25 / 0.91 *a*
Arable	0.40-0.58 / 0.50 *b*	0.29-0.89 / 0.59 *b*	0.31-0.92 / 0.59 *b*	0.18-0.80 / 0.55 *b*
Recreational	0.45-1.13 / 0.79 *a*	0.23-1.37 / 0.99 *a*	0.48-0.87 / 0.63 b	0.33-0.92 / 0.63 *a*
Residential	0.61-1.06 / 0.84 *a*	0.22-0.45/ 0.33 *b*	0.90-2.04 / 1.27 *a*	0.40-1.36 / 0.81 *a*
Industrial	0.13-0.88 / 0.67 *a*	0.35-1.06 / 0.59 a	0.33-1.58 / 0.62 *b*	0.28-0.78 / 0.44 *b*

Table 2.2 Microbial respiration (g C m^{-2} yr^{-1}) of soils (0-10cm layer, litter excluded) in different ecosystems of Moscow region

District (number of sites)	Forest	Meadow	Arable	City
Sergiev Posad (28)	1410	1025	438	674
Shatura (30)	832	1682	517	561
Serpukhov (24)	964	324	517	736
Serebryanye Prudy (22)	N/A	797	482	552

The spatial variability of the qCO2 value was also higher in the urban soils compared to the corresponding natural references, except Shatura district, where high qCO2 variability in meadow and forest ecosystems was likely related to the patchiness of zonal soil cover (Figure 2.3). The MBC/SOC was also sensitive to the land-use with the lowest values in urban industrial zones (Figure 2.4). It should be noted that the urban soils were capable to higher microbial respiration than, for example, the arable ones. Therefore, the potential gas-production activity (CO2 emission) by the urban areas is likely comparable to that of the soils in the non-urban ecosystems.

The contributions of fungi and bacteria to the total microbial biomass in the Eutric Podzoluvisols soil of the forest (C_{org} 4.92%; pH 3.84) and the urban soil of the recreational (C_{org} 3.50; pH 6.16) and industrial zones (C_{org} 3.62%; pH 7.05) in Sergiev Posad district were determined. It was shown that fungi prevailed in the soil microbial biomass, giving 63-80% of its structure. The fungi-to-bacteria ratio of 3.5 for the forest zone, 3.3 for the recreational zone, and 1.4 for the industrial zone, respectively, indicated a significant decrease in the fungal component (by almost 2 times) under the increasing anthropogenic impact.

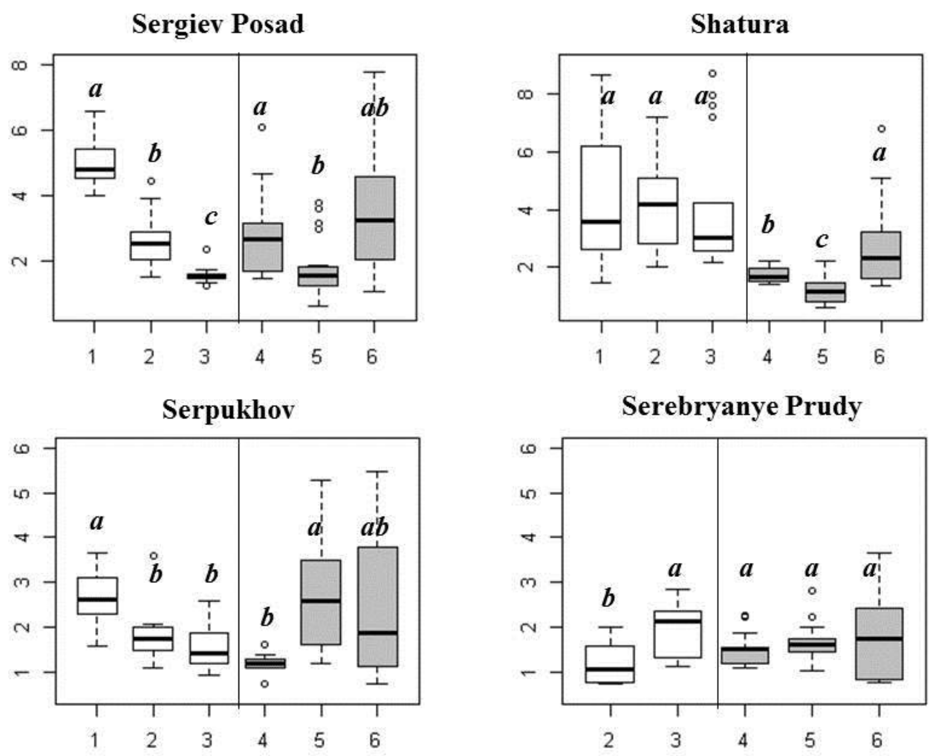


Figure 2.3 Distribution of the microbial metabolic quotient of the soils (0–10-cm layer, (μg CO_2–C mg^{-1} C_{mic} h^{-1}) in different ecosystems and functional zones of Moscow region (the values with different letters differ significantly ($p \leq 0.05$) within each district and its functional zones separately)

Discussions

Natural (non-disturbed), arable (slightly disturbed) and anthropogenically transformed (urban) soils were studied under different bioclimatic conditions of the Moscow Region. Such a spatial-horizontal gradient allowed tracing the changes in the microbial parameters of the soils under various anthropogenic impacts, considering their spatial variability. Microbial activity obtained for the anthropogenically transformed soils were generally lower compared with the natural analogues, which is in good coherence with the other researchers showing a significant decrease of MBC, BR values and fungi-to-bacteria ratio in soils with increasing anthropogenic impact (Beyer et al., 1995; Lorenz and Kandeler, 2006; Gavrilenko et al., 2011).

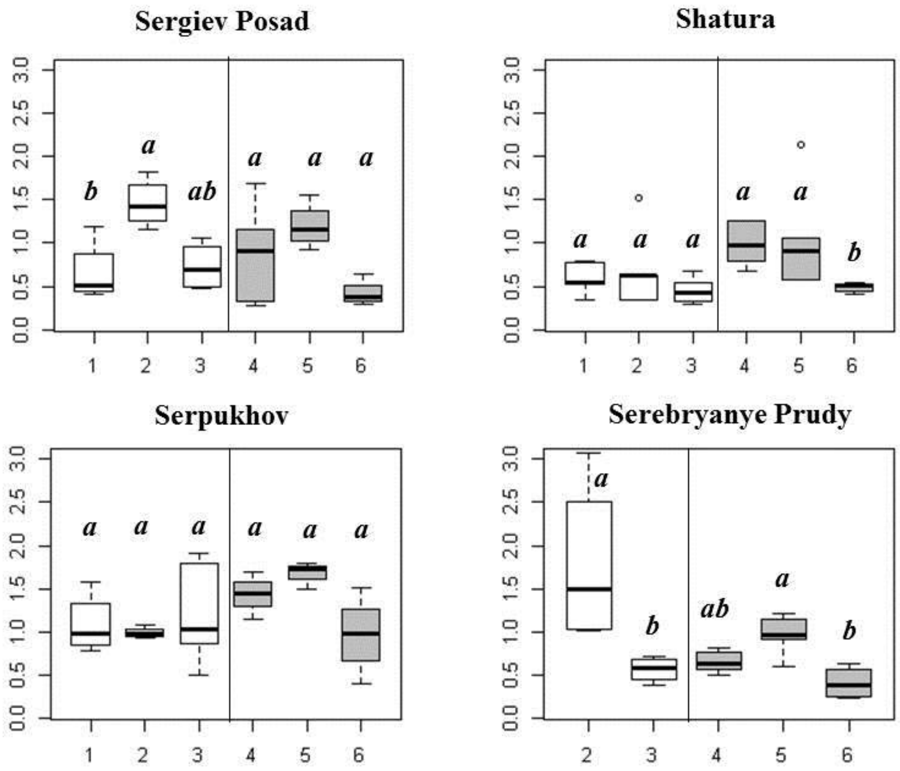


Figure 2.4 Distribution of the MBC/SOC ratio (%) in the soils (0-10cm layer) of different ecosystems and functional zones of Moscow region (the values with different letters differ significantly (*p* ≤ 0.05) within each district and its functional zones separately)

The major part of the soil CO_2 emission results from the activity of heterotrophic soil microorganisms, giving e.g. almost 78% of its total emission for the arable land and 48% for the different-aged fallows (Kurganova et al., 2011). The microbial (basal) respiration of soil determined under laboratory conditions (optimum moisture content, temperature, disturbed structure) is a promising proxy for the potential carbon outflow from soil. Therefore, there is a basis to assess the microbial production of CO_2 upper most biologically active mineral soil. The rate of the microbial CO_2 evolution by 1 g of soil was recalculated per unit of area (1 m^2) of the 10cm thick soil layer. The density of the soil in the calculation was taken equal to 1 g cm^{-3} (Oreshkina, 1988). The found values were the maximum in the soils under woody and herbaceous plants of natural ecosystems and lower by almost 2 times in the anthropogenically transformed soils (arable, city).

According to our calculations, the soils of arable lands and cities of Moscow Region can potentially provide 438 to 736 g C m^{-2} yr^{-1} to the atmosphere. The rate of potential microbial CO_2 emission from the urban soils is comparative to that from the arable ones. Our results are close to ones obtained in long-term and annual field measurements of the CO_2 emission of by the soils in the southern-taiga in Moscow Region, giving 347-613 g C m^{-2} yr^{-1} for the arable land and the young fallow and 845 g C m^{-2} yr^{-1} for the sown meadow (Kurganova et al., 2011). When recalculated to the district areas, the highest emission of CO_2 was obtained in Sergiev Posad and Serebryanye Prudy districts (317.8 and 288.8 thousand tons C yr^{-1}), which was twice as high as in Shatura and Serpukhov districts (140.0 and 178.5 thousand tons C yr^{-1}). On average the CO_2 emission from urban soils was 26% of the emission from the arable ones with 59% in the Sergiev Posad district. Considering that so far urban areas give less 10% of the region but extent of urban areas is continuously growing, the importance of urban areas as a potential source of CO_2 emission will increase.

2.4.3. Spatial-temporal variability of in situ respiration in urban soils of south-taiga and forest-steppe vegetation zones

Introduction

Urban topsoils have high potential to emit CO_2 through intensive mineralization of composts and turf-based mixtures used in their formation (Kurbatova et al., 2004; Groffman, 2004). The rate of urban soil's respiration is determined by its main components: heterotrophic respiration of microorganisms and autotrophic root respiration (Kuzyakov and Larionova, 2005; Chapin et al., 2006; Gomes-Casanovas et al., 2012). Considerable amount of introduced vegetation species including green lawns contributes to root respiration (Milesi and Running, 2005; Svirejeva-Hopkins et al., 2006), whereas considerable difference in biomass quantity and structure between urban and reference zonal soils determines differences in heterotrophic respiration (Lysak et al, 2013; Vasenev et al., 2012).

Total soil respiration and its components are highly variable in space (Bahn et al., 2010; Kuzyakov and Gavrichkova, 2010). High heterogeneity reported for urban areas (Prokofyeva and Stroganova, 2004; Vasenev et al., 2013b) contributes to this variability. Spatial variability of urban soil respiration can be influenced by both conventional (climatic, vegetation) and urban-specific (soil sealing functional zoning, soil pollution and physical disturbance) factors. Contrast anthropogenic pressure represented by different functional zones is a key urban-specific driver of spatial heterogeneity. Industrial, residential and recreational zones are very different in percentage of the sealed areas, the level of anthropogenic disturbance, chemical and biological soil features, which determines difference in soil respiration between functional zones. At the same time, urban soils function in specific bioclimatic conditions and thus bioclimatic driver also contributes to soil respiration and it variability.

It is critical to understand driving factors influencing carbon fluxes in urban soils under various bioclimatic and management conditions to be able to model urban carbon and to analyze contribution of urban soils to regional and global carbon balance. In order to analyze contribution of “bioclimatic” and “urban-specific” factors to urban soil’s respiration we made a parallel comparative analysis of CO_2 efflux from urban soils of three contrast functional zones located in cities from different bioclimatic zones.

Materials and methods

Respiration was measured in urban soils in two cities: Moscow and Kursk. Moscow (N55°50'; E37°33') is located in the south-taiga zone. Climatic conditions in Moscow are humid continental with average July temperature 19.1°C and average January temperature of –14.0°C. In winter, temperature normally drops to approximately −10.0°C, though there can be periods of warmth with temperature rising above 0.0°C. The average number of days with temperature below zero varies from 151 to 197 with the clear tendency to decrease during the last decades. The average annual precipitation is close to 700mm (Naumov et al., 2009). Relief is represented mainly by moraine hilly plain and moraine loam is the main parent material. Zonal Eutric Podzoluvisols are the most diffused zonal soil type in the area (FAO, 1988; Shishov and Voitovich, 2002). Kursk (N51°54'; E36°10') locates 500 km to the SSW from Moscow. Its climate is temperate continental (average July temperature 20.9 °C and average January temperature of – 6.4°C) with drier conditions than in Moscow (average annual precipitation less than 600mm). Natural vegetation is represented by forest-steppe species. Orthic Luvisols and Luvic Chernozems dominate in the region (Dobrovolsky and Urussevskaya, 2004).

Sampling plots were chosen in the industrial, recreational and residential functional zones of each city. Industrial areas were represented by green lawns near gas station and in the sanitary-hygienic zone of the rubber factory. Residential zone referred to university campuses, whereas recreational zones were represented by parks. Two urban forests (one in each city) were chosen as a semi-natural references. Soil respiration was measured by Li-820 IRGA (LI-COR Biosciences, USA) in 5-10 points from each experimental plot. Measurements were taken for the period of June-November 2013 to capture spatial variability. Measuring soil respiration was followed by observations of soil temperature and moisture.

<u>Results</u>

High temporal and spatial variability in soil respiration was reported for both of the settlements. Temporal dynamics was positively correlated with soil temperature, although correlation with soil moisture was not significant. Both in Kursk and in Moscow the highest respiration was obtained at the end of July and the beginning of August and the lowest – at the end of October. Average respiration in the Kursk city was 10-15% higher than one in the Moscow city for major part of the summer period, although the surpass reached 50% at the end of September-October, when the lowest temperatures and the highest moisture over the whole observation period was reported (Figure 2.5). Significant difference was found between averaged soil respiration in different functional zones within the cities. For both settlement average soil respiration from more disturbed industrial and residential areas were 20-50% higher than from recreational zones and urban forest where anthropogenic disturbance was less (Figure 2.6).

In spite of the reported high spatial-temporal variability, significant difference in average soil respiration was found between urban functional zones and urban forests. The respiration rates obtained for urban areas were almost two times higher than for the semi-natural references. In contrast, the difference between average soil respiration in the Moscow and Kursk cities was not statistically significant (Figure 2.7.). These outcomes allow proposing intrazonal features in urban soils' respiration. Factorial ANOVA results confirm this hypothesis. "Urbanization" explained 27% of the total variance. "Bioclimatic" conditions were not significant and contributed to less than 1% of total variance.

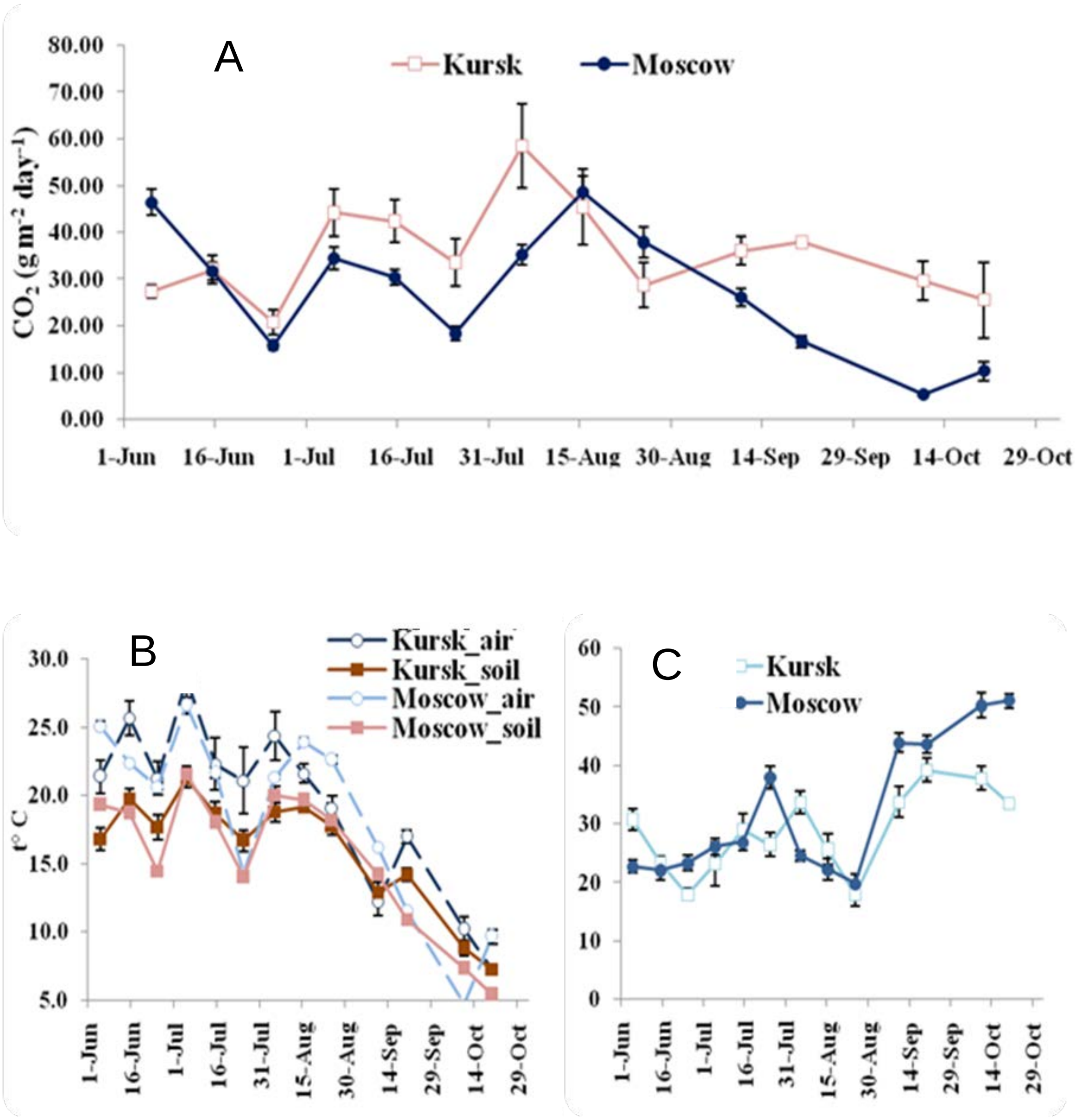


Figure 2.5 Temporal dynamic of in situ CO_2 emission (A), soil and air temperature (B) and soil moisture (C) averaged for analyzed soils in the Kursk and Moscow cities

<u>Discussion</u>

In our study we observed higher respiration in urban soils in comparison to urban forest which we used as a semi-natural reference. This outcome, is in accordance with the few available comparable studies in Arizona and Baltimore (USA) (Koerner and Klopatek, 2002; Kaye et al., 2005), Shanghai and Nanjing (China) (Sun et al., 2009; Zhang el al., 2010), which also report higher soil respiration in urban soils in comparison to agricultural and natural ones. Different factors, explaining this tendency are given in literature. Some authors explain this by higher SOC contents reported for urban soils (Pouyat et al., 2009; Zircle et al., 2011), including artificial organic substrates (compost and sewage materials) added during soil reclaiming and greenery work (Lorenz and Lal, 2009; Beesley, 2012) and easily mineralizable by microorganisms. Another explanations links higher urban soil respiration rates to increase of average soil and air temperatures due to urban "heat island effect" (Davidson, 1998) and alteration of soil physical properties (Chen et al., 2013).

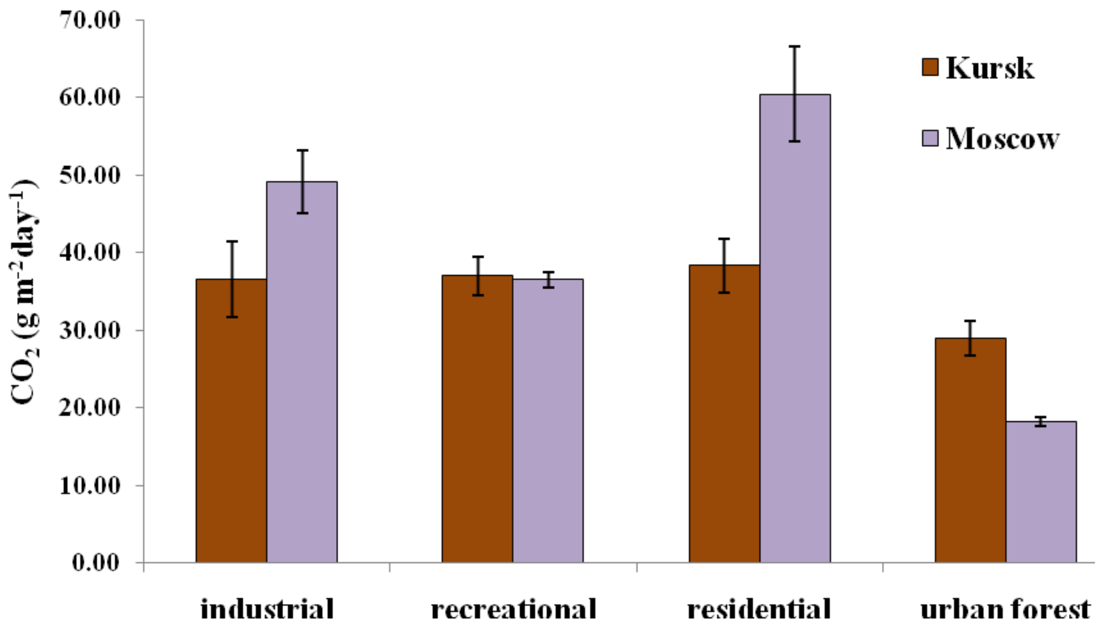
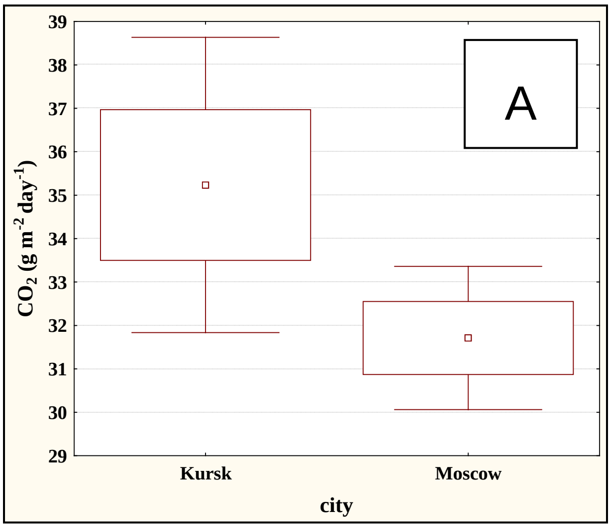


Figure 2.6 Averaged CO_2 emission from soils located in different urban functional zones and in urban forests of the Moscow and Kursk cities

Temperature effect is rather likely in our case since in average for the season microclimate in urban forests in both cities was cooler than in urban functional zones, which is the result of difference in vegetation and higher opacity of urban forest. However, difference in temperatures varied within the season but wasn't higher than 1.0-1.5°C and hardly could be the only facture distinguishing considerable surpass of urban soil respiration over urban forests. Most likely higher respiration from urban soils compared to urban forests was caused by additional lawn management (fertilization, cutting) and physical disturbance. High disturbance creates stressful; environmental conditions for soil microorganisms and stimulate metabolism over transforming soil carbon into microbial biomass (Lysak et al., 2000). This outcome is in good coherence with the previous case study, where lower values of microbial respiration were obtained in the urban soils compared to natural ones.



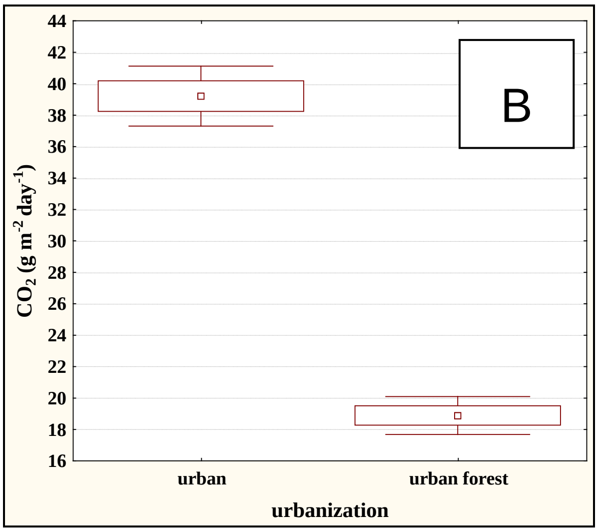


Figure 2.7. Mean, standard deviation and 95% confidence interval of CO_2 emissions averaged for Moscow and Kursk cities (A) and for urban functional zones and urban forest plots (B).

2.5. Conclusions

Urbanization is among the most important current land-use trends and its role will likely grow in the future (Pickett et al, 2011). Urbanization alters stocks and fluxes of energy and matter and results in irreversible changes in vegetation and soil cover (Milesi and Running, 2005; Scalenghe and Marsan, 2009; Vasenev et al., 2013c). However, carbon stocks and fluxes of urban soils lack attention and our understanding of their spatial-temporal variability and contribution to the regional carbon budget remains very limited and uncertain. In this chapter we discussed the main current achievements and gaps in studying carbon stocks and fluxes in urban soils. Especial attention was given to the methodological aspects of studying spatial-temporal variability of urban soil carbon, illustrated by the multiple scale case studies.

In our research, we demonstrated that the extremely variable urban environment, both in terms of management practices and anthropogenic disturbance, leads to very high spatial heterogeneity of carbon stocks and fluxes. Significant difference of carbon stocks and fluxes in urban soils and agricultural or natural ones is another key outcome of comparative analysis between ecosystems and bioclimatic zones. Considering high internal variability discussed above this significant difference of carbon stocks and fluxes in urban and nonurban soils may represent intrazonal features in urban carbon balance rather than zonal ones. However, we did not obtain similar spatial trends for different parameters of carbon cycle within urban areas. Soil microbial biomass and microbial respiration decreased when anthropogenic influence increased with the lowest values reported for the most disturbed industrial zones. In contrast, *in situ* soil respiration in industrial zones was higher than in residential and recreational ones. Apparently, microbiological activity parameters are sensitive to stressful conditions of urban environment and low values of microbial carbon and respiration indicate unfavorable conditions for microbial community. Higher *in situ* soil respiration is a factor of physical disturbance and dissipative metabolism vs. immobilization of carbon into microbial biomass. In other words, urban environment creates conditions for high momentary carbon efflux, which can significantly decrease in future if new artificial adding of carbon to urban soils does not occur.

Although our result represent an overview of a limited number of individual studies and though remain rather uncertain they contribute to understanding of carbon stocks and fluxes in urban soils and their spatial-temporal variability. Obtained variability of carbon stocks in time and space in urban areas requires a better analysis and needs to be incorporated in environmental assessment practices. Some studies report a considerable potential of urban soil to store carbon (Poyat et al., 2006; Golubiewski, 2006), which can question the widely assumed concept of urbanization as a threat to climate change (Kalnay and Cai, 2003; Grimm et al., 2008).

3. URBAN SOIL ORGANIC CARBON AND ITS SPATIAL HETEROGENEITY IN COMPARISON TO NATURAL AND AGRICULTURAL AREAS IN MOSCOW REGION

ABSTRACT

Soils hold the largest carbon stock in terrestrial ecosystems. Soil organic carbon (SOC) is formed under a combination of bioclimatic and land-use conditions. Therefore, one would expect changes in SOC stocks with land-use changes like urbanization. So far, the majority of regional studies on SOC exclude urban areas. The urban environment has a unique set of specific features and processes (e.g. soil sealing, functional zoning, settlement history) that influence SOC stocks and its spatial variability. This study aims to improve our understanding of urban SOC in comparison with agricultural and natural areas for the case of Moscow Region (Russia). SOC was studied in different land use types, soils, and urban zones through stratified random sampling. Samples of topsoil (0-10cm) and subsoil (10-150cm) were taken at 160 locations. SOC stocks were significantly higher in urban areas compared to non-urban areas (3.3 over 2.7%). Further analyses proved that the difference can be explained by the so-called “cultural layer”, which is the result of human residential activity and settlement history. SOC stocks in the urban environment presented a very high spatial heterogeneity with standard deviations of urban SOC considerably higher than those for agricultural and natural areas. Soil depth, soil type and land-use factors had a significant influence on SOC variability determining more than 30% of the total variance. SOC stocks in urban topsoil were mostly determined by soil type. In natural and agricultural areas soil type and land-use determined SOC stocks. The results confirm the unique character of urban SOC and the need to reconsider established scientific and management views on regional SOC assessment, taking into account the role of urban carbon stocks.

Based on:

Vasenev V.I., Stoorvogel J.J., Vasenev I.I. 2013. Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in Moscow Region. Catena 107: 96-102.

3.1. Introduction

Terrestrial ecosystems are a major player in the global carbon cycle, acting as carbon stocks and carbon sources (Ouimet et al., 2007). Soil organic carbon (SOC) is the largest carbon stock in terrestrial ecosystems accounting for about 2000 PG C (Janzen, 2004). Carbon sequestration is a widely accepted soil ecosystem function (MA, 2005; Blum, 2005; Kudeyarov et al., 2007). Regional analysis of SOC stocks is important and receives increasing attention in, for example, land-use planning (Krogh et al., 2003; Gruniberg et al., 2010; Phachomphon et al., 2010). Although quite a few studies focus on analyzing and mapping SOC for natural and agricultural areas (Guo and Gifford, 2002; Zhou et al., 2007; Stoorvogel et al., 2009), urban areas are often excluded from these regional carbon assessments. General literature indicates various factors to influence SOC variation in a region: soil type (Dobrovolsky and Urussevskaya, 2004), land-use (Lal, 2002; Zhou, et al, 2007), and the level of urbanization (Lorenz and Lal, 2009; Poyat et al., 2006). So far, very little is known about SOC in urban environments. However, urbanization is now one of the predominant pathways of land-use change (Saier, 2007; Seto et al, 2011). In contrast with the global average of 2%, regionally urban lands can occupy up to 10% and their total extent is expanding (Denisov et al., 2008; Pickett et al., 2011). Therefore, it is necessary to understand the contribution of urban soils to the regional SOC stocks.

The urban environment can be characterized by a number of specific features and processes that influence soil formation and functioning (Imhoff et al., 2004; Vrscaj et al., 2008). Soil movement and transformation during construction and greenery work, functional zoning, soil sealing, and settlement history determine the SOC stocks in urban soils with extremely high spatial variability (Prokofyeva and Stroganova, 2004). In contrast to the often gradual changes in natural areas, urban soils may exhibit abrupt changes due to the anthropogenic influence. The spatial heterogeneity is further complicated by a specific profile distribution. Profiles of typical urban soils may display two SOC maximums (Gerasimova et al., 2003; Lorenz and Lal, 2009). The first one is connected with humus-accumulative horizon and the second one corresponds to the so-called “cultural layer”.

The concept of the cultural layer originates in archaeological research, where it was used to define the age of artifacts and describe the settlement history (Avdusin, 1980; Alexandrovskiy et al., 1998). Afterwards the cultural layers of several ancient Russian towns were studied as part of soil morphological research (Kaidanova, 1992; Sycheva, 1994). The cultural layers and soils buried under them were shown to be a single complex, developing in time (Sycheva, 1994). A number of specific soil features, such as a high level of heavy metals' accumulation and soil microbiological communities, non-typical for topsoil were described for cultural layers (Evdokimova, 1986; Marfenina et al., 2008). From a carbon stock perspective, the cultural layers include wooden remains, coal and buried non-urban horizons (Prokofieva and Stroganova, 2004) (Figure 3.1). Organic carbon contents in the cultural layer may be as high as 3-5% or even more (He et al., 2009; Dolgikh and Alexandrovskiy, 2010). Their depth depends on the age of the settlement and varies from 10cm to several meters (Alexandrovskaya and Alexandrovskiy, 2000). So far, most of carbon assessments focus mainly on topsoil (Nilsson et al., 2000). However, ignoring this cultural layer may lead to a considerable underestimation of the SOC stocks.

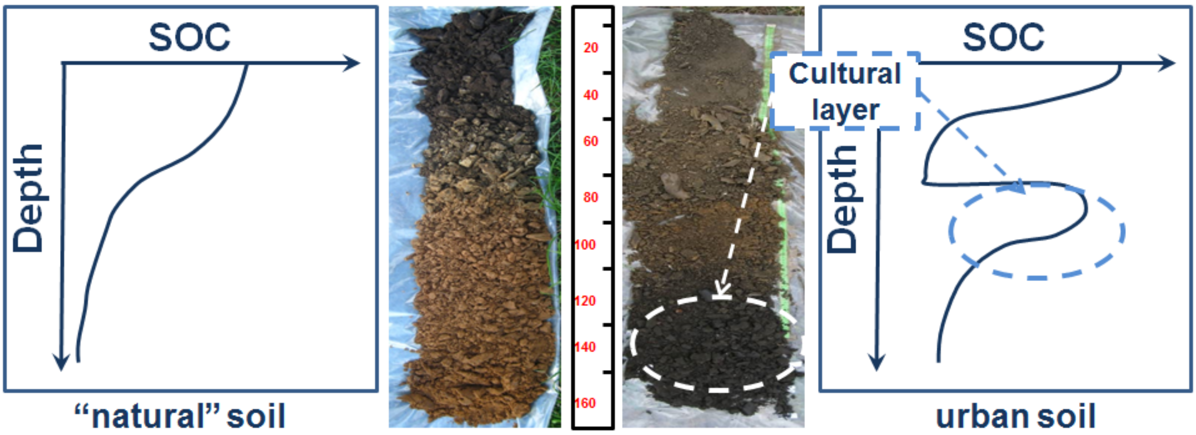


Figure 3.1 Sketch of SOC concentrations' profile distribution for urban and natural soils

This paper aims to provide insight into the importance of urban SOC compared to agricultural and natural areas. In addition it tries to identify and analyze the principal factors influencing the spatial variability of SOC stocks. The study was implemented in Moscow Region that due to its high level of urbanization provides an excellent test case.

3.2. Materials and methods

3.2.1 The study area

The Moscow Region locates in the European part of Russia (55° N; 37° E) covering 46.700 km^2. Four main zonal soil types are found in the region: Orthic Podzols in the north, Eutric Podzoluvisols soils in the center, Orthic Luvisols and Luvic Chernozems in the south. In addition intrazonal Dystric and Eutric Luvisols are located in the flood-plains of the Moscow and Oka rivers (Shishov et al., 2004). SOC concentrations in the topsoil of natural areas vary from 1-2% in Eutric Podzoluvisols up to 6-7% in Luvic Chernozems (Shishov and Voitovich, 2002). The spatial variability of SOC is mainly caused by the variability in soil-forming factors: relief, parent material, climate, vegetation and human influence. The territory of Moscow Region has a plain relief ranging from 100 meters above sea level in the East to 300 meters above sea level in the North and West. The parent material includes moraine loam and clay in the North and center, fluvioglacial sands in the East, and cover loam in the South. The climate of the region is temperate continental with a mean annual temperature of 5°C in Moscow city and 3°C outside the city. Average annual rainfall varies from 780mm in the North to 520mm in the South. The vegetation zones (south-taiga, deciduous forests and steppe-forest plant zones) strongly correlate with climatic conditions in the area. Climate and vegetation are supposed to be main factors behind the variability of natural landscapes (Dobrovolsky and Urussevskaya, 2004). At the same time, anthropogenic factors (land-use, urbanization etc.) play an important role in soil formation. The anthropogenic changed landscapes (e.g. agricultural land, fallow land, and urban land) occupy nearly 60% of the territory. The urban area currently occupies more than 10% and is rapidly increasing. For instance, it has risen from around 7% in 2000 to 8.5% in 2006 (Kachan et al., 2007) and in 2012 the area of Moscow city is expected to more than double according to governmental decision (Resolution of Moscow government #372 from December 12th 2011).

3.2.2 Methodology

Sampling design

A stratified random sampling design was implemented in order to capture the heterogeneity of landscapes, and the variation in urban and non-urban land-use. The different strata were identified on the basis of soil type, land use, and functional zones. Four towns in the Moscow Region were chosen in such a way, that each of them represented one of the four soil types. In addition, the Moscow city, located in the area of Eutric Podzoluvisols, was included in the study. The extent and population of the Moscow city exceeds all other settlements in the region. For more detailed analysis the territory of the Moscow city was split into four subareas on the basis of the age of settlement. The central part of the Moscow city was settled more than 500 years ago whereas its suburbs are much younger. On the basis of available data of historical borders within the age of the urban areas inside the city was estimated. The characteristics of the different settlements and the Moscow city are described in Table 3.1. In each of the settlements, three contrasting functional zones were studied: residential, recreational, and industrial. For each settlement, three common non-urban land-use types in the neighborhood (3-5 km from the city border) were also analyzed: agricultural, fallow/pasture, and nature. Samples from the functional zones were taken in Moscow within the three districts outside the central district. In each settlement five plots were chosen representing each functional zone. In total 155 plots were sampled: 45 in the Moscow city and 110 in the Moscow Region (Table 3.2). Inside each stratum sampling plots were selected randomly. For each plot five topsoil (0-10cm) samples were taken from a $2m^2$ square plot (corners and center). At the center of the plot a subsoil (10-150cm) sample was taken. All samples were taken with a standard Edelman auger. The sampling design covers only the open areas of Moscow Region, as no samples from sealed soils were taken. In the analysis to the driving factors behind SOC differences sealed soils will be ignored.

Table 3.1 Characteristics of settlements studied and Moscow city

Settlement	Area (km^2)	Population (*1000)	Age (years)	Zonal soil type
Dubna	72	63	<50	Gleyic Podzoluvisols
Voskresensk	47	104	50-200	Eutric Podzoluvisols
Pushino	18	20	<50	Haplic Greyzems
Ser. Prudi	4	9	200-500	Haplic Chernozems
Moscow city	1097	10 381	50-900	Eutric Podzoluvisols

Table 3.2 Sampling locations in Moscow region for different strata.

	Non-Urban			Urban		
	Agriculture	Fallow	Forest	Residential	Recreational	Industrial
Moscow left bank	-	-	-	5	5	5
Moscow right bank	-	-	-	5	6	5
Moscow river valley	-	-	-	5	5	5
Moscow - central				4		1
Dubna	-	5	5	5	5	6
Voskresensk	5	5	5	5	5	5
Pushino	5	5	5	9	5	1
Ser.Prudi	5	5	-	6	5	4

<u>Laboratory analysis</u>

All samples were air-dried and roots and plants fragments were removed. Subsequently, the samples were sieved (1mm) and pulverized using an agathic mortar. Afterwards the organic carbon content in prepared soil samples was measured using the dichromate approach with spectrophotometric end point detection (Turin approach with Nikitin modification (Vorobyova, 1998)) in three replications.

Analysis of the driving factors

The dataset provides SOC stocks for a wide range of conditions. Various factors may have an impact on regional SOC variability. It is necessary to distinguish these driving factors in order to analyze their influence. The influence of urbanization on SOC was expected to be relevant and thus was analyzed first. Considering the widely accepted linkage between SOC and soil type, four zonal soil types (Orthic Podzols, Eutric Podzoluvisols, Orthic Luvisols and Luvic Chernozems) were included into analysis of variance. Spatial variability of SOC was complicated by its profile distribution. In order to illustrate SOC profile distribution the ratio between subsoil organic carbon (SS) and topsoil organic carbon (TS) was estimated. In the dataset we were dealing with settlements of different ages. We studied the impact of the age of the settlements after classifying the settlements into 4 age groups: young (less than 50 years), average (50-200 years), old (200-500 years) and very old (more than 500 years old). Quite a few studies show the impact of land-use on SOC (Lal, 2002; Zhou et al., 2007; Kurganova et al, 2011). Urban or non-urban land-use may have a predominant impact, considering the principle difference in land-use history and intensity, soil-functioning conditions and anthropogenic pressure. Influence of widespread non-urban land-use types (forests, natural pastures and arable lands) and contrasting urban functional zones (recreational, residential and industrial) was studied to analyze the contribution of the "land-use" factor to regional SOC variability. Basing on distinguished driving factors, a factorial analysis was performed.

Statistical analysis

Descriptive statistics and correlation matrixes were used to process the data and to investigate SOC variability within and outside categories, distinguished by grouping factors. Significance of difference between SOC in topsoil and subsoil, and between urban and non-urban areas, was checked by a group independent t-test. In order to check the assumptions of normality for the analysis of variance (ANOVA) QQ-plots were created. The homogeneity of variance was checked using Levene's test. The independence of the data was appropriately addressed by the sampling design. Main-effect and factorial ANOVA was implemented to analyze the impact of the factors. Predictive power of ANOVA was characterized by determination coefficients R^2 and R^2_{adj}. An F-protected LSD test was used to check for significance of differences between the groups.

3.3. Results and discussion

3.3.1 Importance of urban SOC

The average SOC (0-150cm) in urban areas (3.3±1.9%) turned out to be significantly higher ($p<0.05$) than in non-urban areas (2.7±1.6%). Although SOC in urban areas is generally excluded from the regional assessment (e.g. Burghardt, 2002; Schaldach and Alcamo, 2007, Schulp and Verburg, 2009), this study shows that cities can have considerable carbon stocks. This conclusion is confirmed if we look at individual soil types. On Luvic Chernozems and Eutric Podzoluvisols, SOC contents in urban areas were even significantly higher than in non-urban areas ($p< 0.05$) (Figure 3.2). For the Orthic Luvisols, urban SOC was not significantly higher and only for Orthic Podzols SOC of the settlement was lower (but still considerable). In the latter case some of the samples in non-urban areas were taken in moist forests conditions with very high (up to 7%) SOC concentrations.

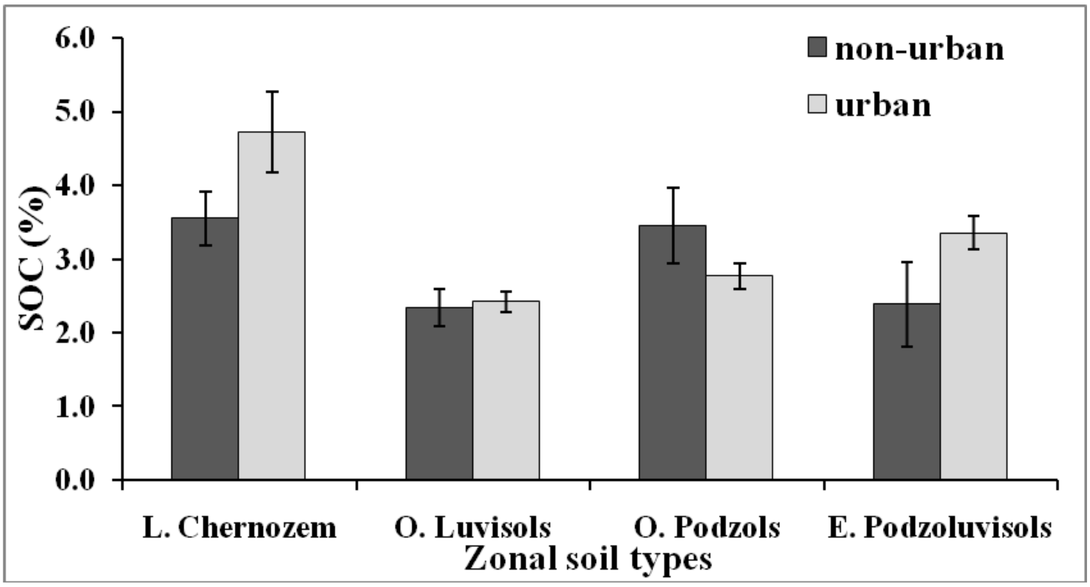


Figure 3.2 Comparison of urban and non-urban SOC (means and standar error) for different soil types in the Moscow region

In order to obtain insight into the reason behind higher average values of SOC in urban areas compared to natural and agricultural ones, SOC contents in topsoil and sub-soil was analyzed separately. The analysis showed that that there is no significant difference between topsoil SOC in urban and natural areas (Table 3.3), whereas SOC in the subsoil differs significantly.

Table 3.3 Comparison of mean SOC for natural and urban areas in topsoil and subsoil in Moscow region

		N	mean	stdev	t-test	df	p-value
Topsoil	natural	50	4.22	1.98	0.92	160	0.36050
	urban	112	3.78	1.80			
Subsoil	natural	50	1.72	0.69	2.93	156	0.00385
	urban	108	2.30	1.30			

Thus the difference in total SOC stocks between natural and urban areas was caused by subsoil SOC. This confirms the importance of the "cultural layer" in urban SOC stocks. Whereas for the vast majority of natural and agricultural soils observed SOC for subsoil was 2-4 times lower than in the upper horizons, subsoil SOC within settlements was often comparable to, and in a few cases even exceeded, topsoil SOC. Considering significant difference in thickness of the layers (10cm for topsoil observed and from 30cm to several meters for the 'cultural layer'), this outcome definitely illustrates the necessity to consider the SOC profile distribution. The SOC profile distribution can be illustrated by the ratio SS/TS of subsoil SOC (SS) over topsoil SOC (TS). SS/TS values lower than 1 demonstrates typical natural SOC distribution with the main carbon concentration in topsoil, whereas values close or higher than 1 refers to considerable role of subsoil carbon (Figure 3.3).

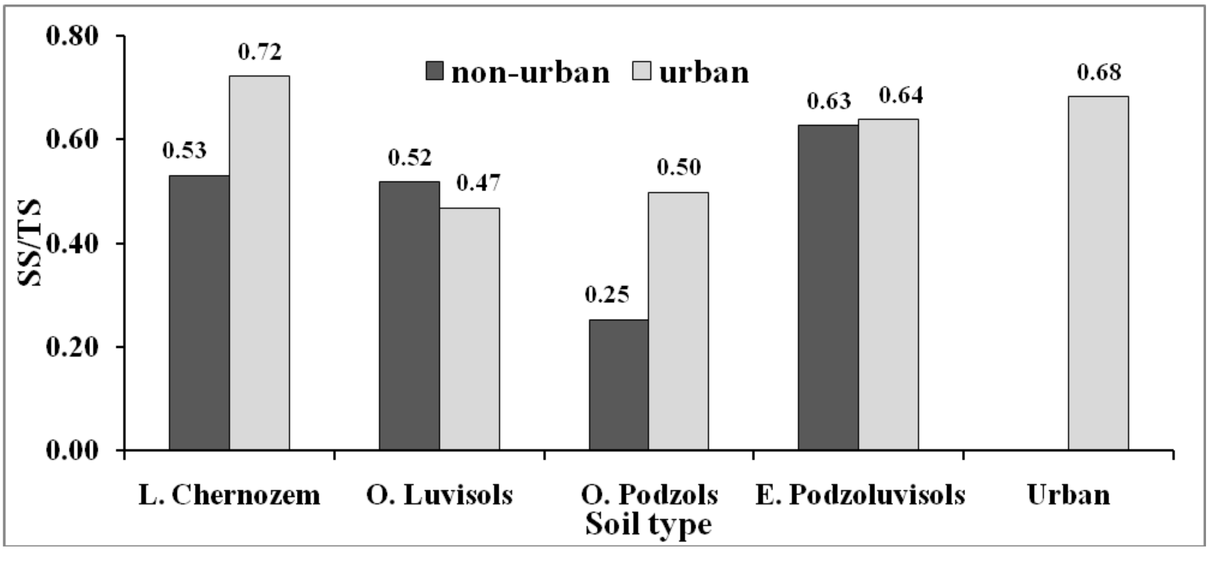


Figure 3.3 Urban and non-urban values of SS/TS ratio for different soil types in the Moscow region

For the Luvic Chernozems and Orthic Podzols zones, the SS/TS ratio in urban areas was significantly higher than one for non-urban. In the Eutric Podzoluvisols and Orthic Luvisols zones the ratio differences between urban and non-urban soils were not significant. SS/TS for the Moscow city (for which only urban soils were sampled) amounted to 0.68, which was considerably higher than for any non-urban area observed. Such a high value obtained for the Moscow city actually means the difference between subsoil and topsoil SOC amount just to 40%. It might be explained by a long history of anthropogenic influence that resulted in the formation of thick cultural layer rich with organic carbon.

As the "cultural layer" is a result of settlement history, it is logical to assume a connection between urban SOC and the age of the settlement. For the topsoil such a correlation was very weak (r=0.1) as a result of the intensive transformation of topsoil in the urban areas. Renewal of turf and sand substrate on green lawns, mineral fertilizers, and ice-melting salt on the roads may have a considerable impact on the topsoil. However for the subsoil the correlation between age of the settlement and SOC is significant (r= 0.36). The only exception from the rule is the central part of the Moscow city (800 years old) for which higher values of SOC could have been expected (Figure 3.4). Perhaps, the sampling depth (10-150cm) was not enough to reach the cultural layer, which may be located as far as 3-4m under the surface in the ancient parts of the city. In addition, the central part of the Moscow city is obviously the most difficult area for sampling resulting in only 5 samples (four of them from recreational areas). Therefore, the data characterizing the 800 year old settlement is less representative.

Considering that several settlements represented one age category and one soil type, multi-collenearity problems are expected. To resolve these problems, we looked at urban SOC relative to SOC in the meadow areas for the different settlements. The meadow areas were chosen as a standard for comparison as far as they are typical natural landscapes for the region and they were the only non-urban areas, sampled in the neighborhoods of all settlements. The relationship between this relative change with urbanization and the age of the settlement is presented in Figure 3.5. For the topsoil the shape of the curve has changed. However no correlation between SOC and age was found. As for the subsoil, the trend remained almost the same. It may be concluded, that settlement's history influences mainly subsoil SOC, whereas topsoil SOC is more dependent on land-use or zonal soil type. Thus, it was demonstrated, that urban carbon stocks, mainly concentrated in subsoil, make a considerable contribution to the regional carbon balance and may have a remarkable influence on spatial variability of SOC in the region.

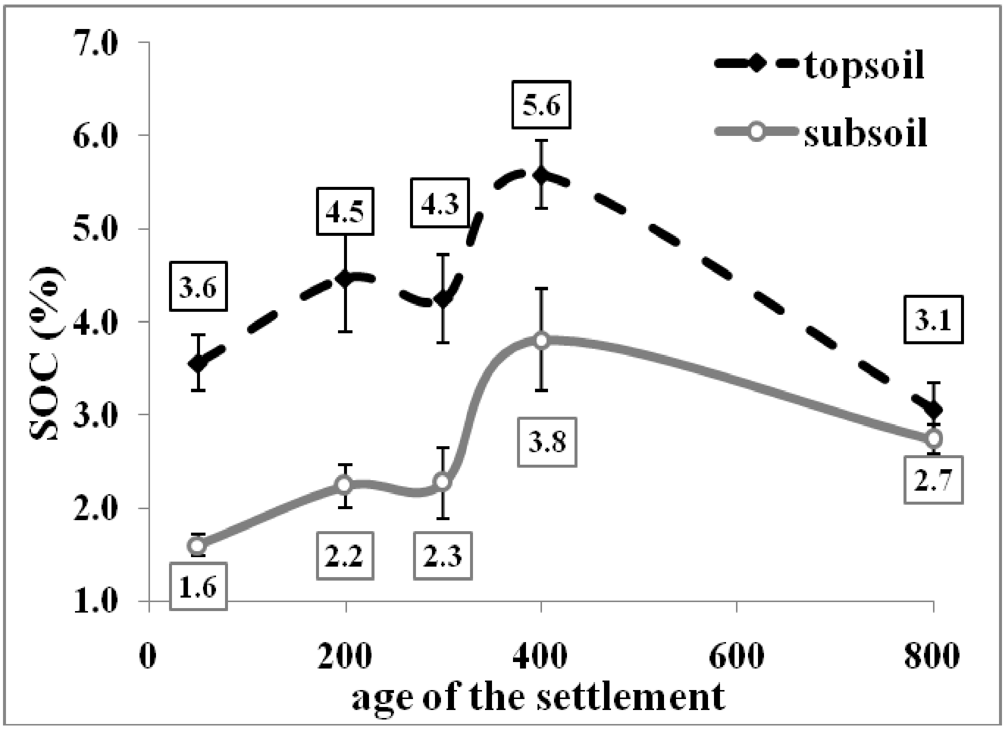


Figure 3.4 SOC concentrations (mean and standard error) for settlements of different ages in the Moscow region

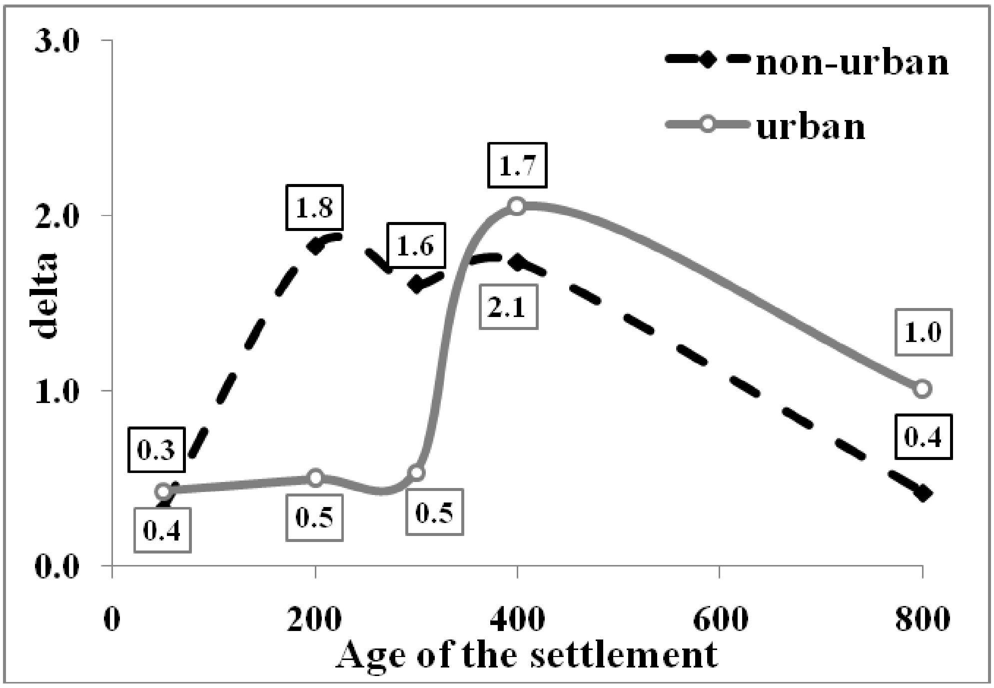


Figure 3.5 Increase of SOC concentrations (means) in urban areas compared to meadow areas (delta) for settlements of different age in the Moscow region

3.3.2 *Spatial variability of SOC in Moscow Region*

Field results confirmed the assumption on high spatial variability of SOC in the Moscow Region. The values of SOC varied from 0.4% to 10.4% with a mean value of 3.1% and a standard deviation of 1.9%. Significant differences between SOC in topsoil (4.1±1.9%) and subsoil (2.1±1.2%) were found ($p<0.05$). Comparison of soil samples, collected in different locations of Moscow Region demonstrated high spatial variability of SOC both for topsoil and sub-soil (Figure 3.6). The standard deviation of SOC was significantly higher in urban areas (1.9%) than for natural areas (1.6%). This can be explained by a set of specific factors (soil sealing, functional zones, contamination etc.) influencing SOC in urban areas in addition to non-specific ones, mainly connected to natural conditions (soil type, relief and climate).

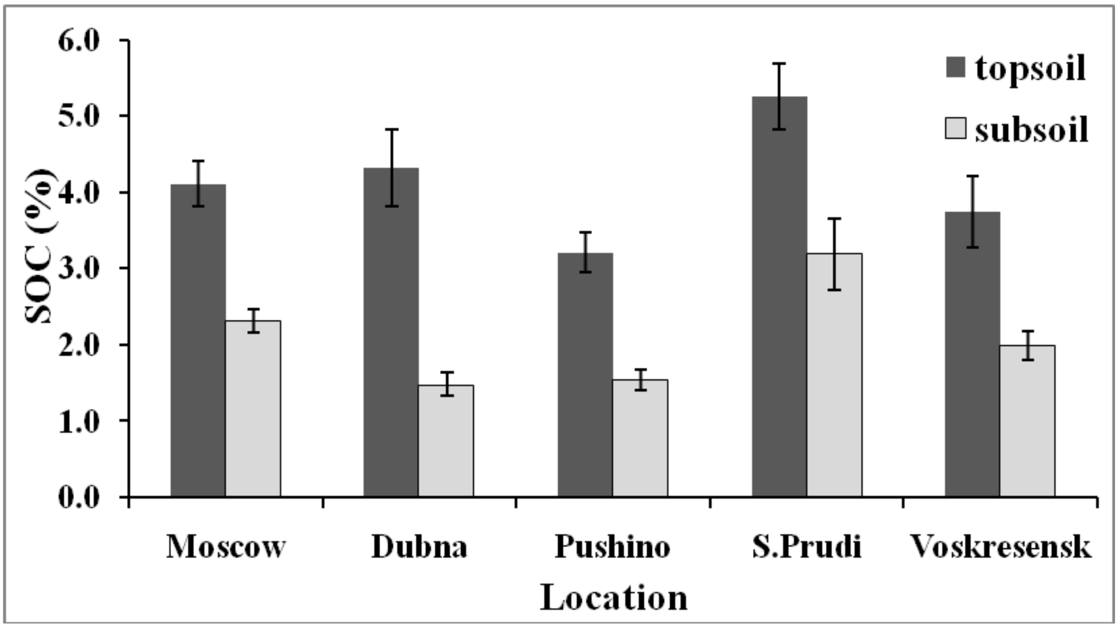


Figure 3.6 Average SOC concentrations (mean and standard error) in different settlements in the Moscow region

The lowest topsoil SOC in non-urban areas was obtained for grey forest soils (2.1±0.3%) whereas SOC contents in Luvic Chernozems (3.8±1.2%) and Orthic Podzols (4.4±1.2%) were significantly higher. As for the subsoil the SOC for Luvic Chernozems and Eutric Podzoluvisols (1.8±0.6% and 1.7±0.1%) were significantly higher than for Orthic Podzols and Orthic Luvisols (1.3±0.3% and 1.1±0.1% correspondingly). General literature reports increases of SOC from Orthic Podzols (1-3%) and Orthic Luvisols (2-4%) to Luvic Chernozems (4-7%) (Dobrovolsky and Urussevskaya, 2004; Nilsson et al., 2000; Ananyeva et al., 2008). The same trend is observed in the area with the Gleyic Podzoluvisols being the exception. This may be explained by the specific rapidly decreasing SOC profile distribution for Orthic Podzols, for which obtained topsoil SOC was the highest comparing to other soil types, whereas subsoil SOC- among the lowest.

The residential areas situated in different soil zones show different results. The highest topsoil SOC was found in Luvic Chernozems and Orthic Podzols (4.6±1.0% and 4.3±1.4%), whereas the lowest topsoil SOC was observed in Orthic Luvisols and urban soils (3.4±1.2% and 2.7±1.0%). For the subsoil SOC contents in Orthic Podzols and Luvic Chernozems zones (3.9±1.1% and 2.5±0.5%) were high and the lowest values were found in the Eutric Podzoluvisols (1.8±0.3%).

The effect of human activity on SOC is land use that mostly influenced the soils for a shorter period than climate and parent material. However, the influence of land use can be very intensive. Urban and non-urban land-use types refer to different types of anthropogenic activity that, in the context of this study, influence SOC. Non-urban land-use types mainly differ in the input of organic matter and the mineralization rates through tillage. Urban functional zones differ through the effects of contamination and sealing. The size of urban functional zones is small but with very high internal variability compared to natural and agricultural land-use. In order to illustrate land-use influence on SOC three non-urban land-use types (forest, natural pastures and arable land) and three urban functional zones (industrial, residential and recreational), situated in sod-podzolic soil zone were compared.

For non-urban areas SOC in natural pastures was lower than in forest areas, but higher than in arable lands both for the topsoil (2.6±0.5%, 3.9±1.3%, and 2.5±0. 6%) and for subsoil (1.7±0.1% , 2.0±0.69%, and 1.5±0.2%). Topsoil SOC in forest was significantly (F-proved LSD- test) higher than for other land-use types although no significant difference was found for subsoil. Higher values obtained for forest SOC in comparison to other land-use types was quite expected. Difference between agricultural and forest SOC, close to 50% corresponds with the results of quite a few similar studies published (Ananyeva et al., 2008; Laganiere et al., 2010; Papini et al., 2011).

3.3.3 Factorial ANOVA results

Since normality, independence and constant variance of SOC distribution were proven, factorial ANOVA was implemented for quantitative analyses of the principal driving factors, influencing SOC variability in urban and non-urban areas. Factorial ANOVA shows a significant ($p<0.05$) effect of “depth”, “soil type” and “land-use type” factors but no significant effect of paired interactions of these factors ($p>0.05$) (Table 3.4). The statistical model was able to explain a large part of SOC variability (R^2= 0.67; R^2_{adj}= 0.42).

An ANOVA was implemented for urban and non-urban areas and topsoil and subsoil separately since significant differences between them were proven above. For urban areas the influence of soil type and land-use and age and land-use was examined. The “soil type” and “age” factors were not included in the analysis at the same time because of the high correlation between these two factors. For the case of urban topsoil “soil type” and “soil type×land-use” were shown significant factors ($p<0.05$) determining 14% and 22% respectively of total variance for the first factor combination. As for the second factor combination both “age” and “land-use” factors and their interaction were demonstrated to have significant influence on SOC variability. They determined respectively 16%, 8% and 18% of the total variance. Both models demonstrated similar levels of determination. In both cases influence of “soil type” and “age” factors dominated over “land-use” factor. As for subsoil “land-use” factor was shown non-significant in both cases ($p>0.05$), whereas “soil type” for the first dataset and “age” in the second case were significant. “Soil type” determined 21% of total variance and “age” factor was responsible for 23%. Determination coefficients were similar in both cases and close to values, shown for topsoil (R^2=0.58; R^2_{adj}=0.24 for the first case and R^2=0.58; R^2_{adj}=0.26 for the second case).

Table 3.4 Factorial ANOVA for total dataset

General effects	df	SS	MS	F	p
Intercept	1	1749	1748.6	849.3	0.00
Depth	1	201	200.6	97.4	0.00*
Soil type	4	92	23.0	11.2	0.00*
Land-use	6	59	9.9	4.8	0.00*
Depth × Soil type	4	11	2.8	1.4	0.24
Depth × Land-use	6	25	4.2	2.0	0.06
Error	298	614	2.1		
Total	319	1134			

For the natural areas the influence of “land-use”, “soil type” and their interaction was examined. The situation was complicated by the fact, that not all land-use types were found on all soil types (Table 3.2). Examples include the forest areas in chernozems and arable lands in podzols that were not found. In order to make the design orthogonal certain land use types and soil types were excluded from the analysis which resulted in 6 factor combinations.

The soil type factor proved to be significant for four of the six cases (66%). It determined 20 to 45% of total SOC variability. Significance of the land-use type was shown for five cases

(83%). It was responsible for 10-40% of total SOC variability. The interaction of soil type and land-use factors was demonstrated to be significant in two cases (33%) and determined from 15 to 25% of total SOC variability. High predictive power of all models was roved by determination coefficients.

Soil type/age, land-use and their interaction distinguished SOC variability for urban topsoil, whereas for urban subsoil only soil type/age had a significant influence and land-use type did not. As for natural areas, influence of soil type and land-use was demonstrated both for topsoil and subsoil.

3.4. Conclusions

Urban soil organic carbon pools remain one of the least known carbon pools. Studies on urban ecosystems have been traditionally ignored by ecologists and soil scientists (Byrne, 2007; Grimm et al., 2008). This study demonstrated the importance of the urban SOC. In the Moscow Region the urban SOC stocks were found to be comparable or higher than carbon stocks of natural and agricultural areas. This contradicts the popular assumption that urban SOC can be ignored. The main source of carbon accumulation in the settlements was found in the subsoil and corresponded to the “cultural layer”. This layer is the result of human residential activity over a long period of time. The combined effect of high SOC contents and significant depth of the cultural layers results in a large carbon stock which has been underestimated before. Significant correlation between age of the settlement and subsoil SOC was demonstrated, thus settlement history was shown to be one of the predominant specific factors distinguishing urban carbon stocks and contributing to SOC spatial variability.

The study revealed a high spatial variability of SOC in urban soils compared to natural and agricultural areas. It may be concluded that the urban lands were responsible for a major part of total variability within the region since SOC standard deviation for them was 2-4 time higher than for non-urban ones. Variability of SOC was the result of specific and non-specific driving factors: soil depth, zonal soil type and land-use type, distinguishing more than 30% of total variance. Influence of soil type dominated for the urban topsoil, whereas for natural and agricultural areas soil type and land-use demonstrated equal influence.

Impetuous expansion of urban land-use is one of the main characteristic features of the 21st century Given that globally at least 0.5% of the land is urban (Schneider et al., 2009) and that SOC contents in the urban areas exceeded non-urban SOC with 20%, 0.6% additional carbon is not considered in global modelling yet. Regionally, this underestimation may be much higher. Thus the contribution of urban areas to carbon assessment should not be neglected, although it is not easy to estimate it accurately considering its high spatial variability. Development of the appropriate approach to consider urban SOC and its spatial variability in the regional carbon assessment is a challenge for further research.

Acknowledgements

The project was partly supported by Governmental Grant # 11.G34.31.0079, the Russian Foundation Basic Research grants # 11-04-01376 and # 11-04-02089. The authors thank Julia Pereverzeva for assistance with soil chemical analysis and Rik Leemans, Oleg Makarov, Tatyana Prokofieva and Nadezhda Ananyeva for valuable suggestions and useful comments.

4 HOW TO MAP SOIL ORGANIC CARBON IN HIGLY URBANIZED REGIONS?

Abstract

Urbanization is among the most impetuous current land-use change trends, resulting in a permanently increasing role of urban ecosystems in regional and global environment. Urban soil organic carbon (SOC) is probably the least understood stocks because of the lack of appropriate methodology to analyze and map it. Cities represent a small-scale patchwork of very contrasting soil features. This creates high short-term spatial variability. Urban-specific factors including size and age of the city, soil sealing and cut-off profiles dominate the anthropogenic soil forming factors. Considering these specific urban environments, our study aimed to adapt the digital soil mapping approach to map topsoil and subsoil SOC stocks in a highly urbanized region. Field SOC data collected for different environmental conditions in the Moscow Region (five soil types and five land-use types 244 mixed samples for topsoil and subsoil) were linked to available auxiliary data, including both traditional (relief, climate, vegetation etc.) and urban-specific (functional zoning, size and history of the settlements) factors. Separate general linear models (GLM) were developed for the three different cases: i) excluding urban areas from the analysis (non-urban model); ii) including urban areas but only considering traditional soil forming factors (conventional model); iii) including urban factors (urban-specific model). Total and specific carbon stocks, spatial variability represented by coefficient of variance (CV %) and the determination coefficient with a validation dataset were compared for the three models. The conventional model dramatically overestimated carbon stocks and underestimated of SOC's spatial variability. Total and specific carbon stocks estimated by non-urban model were 10-15% less than ones given by urban-specific model. The urban-specific performed best and explained more than 30% of total variability. Urban areas showed the highest spatial variability and specific carbon stocks, 90% of which was stored in subsoil. Even when the high uncertainty of the absolute values is considered, urban areas contributed to regional carbon stocks. Considering urban-specific factors to estimate carbon stocks and their spatial variability is thus necessary.

Based on: Vasenev V.I., Stoorvogel J.J., Vasenev I.I., Valentini R. 2014. How to map soil carbon stocks in highly urbanized regions? Geoderma. 226-227. 103-115

4.1. Introduction

Soils provide the largest stock of organic carbon in terrestrial ecosystems (Janzen, 2004) and can act as an important sink or source of carbon (Valentini et al., 2000; Houghton, 2003b; Imhoff et al, 2004). The majority of global assessments identify land use as one of the key factors determining carbon stocks (Baldocchi et al., 2001; Guo, 2002; IPCC, 2005; Chiti et al., 2010). Although urban land use is probably the most intensive one, the contribution of urban soils to regional and global carbon stocks is almost ignored so far (Schaldach and Alcamo, 2007, Schulp and Verburg, 2009). This is rather surprising as urban areas cover more than 0.5 million km^2 globally (Schneider et al., 2009) and with the current rapid rates of urbanization (Seto and Shepherd, 2009). Urbanization changes vegetation and soil cover irreversibly through, for example, the translocation of soil material for construction, greenery work, and soil sealing and will therefore impact its carbon stocks (Scalenghe and Marsan, 2009; Elvidge et al., 2004; Milesi and Running., 2005). The urban areas store a large, but poorly understood stock of carbon (Golubewski, 2006; Raciti et al., 2011). Comparative analyses between the topsoil in rural and urban sites have demonstrated a higher or equal capability of carbon storage in urban areas compared to rural or natural ones (Qian et al., 2010; Zircle et al., 2011). The differences may be even bigger if, in contrast to many studies (Pouyat et al, 2006; Raciti et al., 2008), the carbon stocks of the subsoil are considered (Lorenz and Lal, 2009; Vasenev et al., 2013c). Although urban carbon stocks are found to be important, the actual stocks and variability are still often unknown (Jobbagy and Jackson, 2000; Liebens and Van Molle, 2003; Lal, 2004; Stockman et al., 2013). Urban soils present a diversity of specific features and processes, like zoning, combustion, fertilization, sewage release (Lehman and Stahr, 2007), soil pollution, and compaction (Gerasimova et al., 2003; Prokofieva and Stroganova, 2004). These processes may result in high short-distance heterogeneity and patchiness.

Conventional soil surveys often excluded urban areas and focused on land use planning in rural areas. In urban planning deeper layers are more important than surface layers while dealing with the foundation of construction. The initial lack of interest in the urban soils can be illustrated by the fact that for a long period of time they were almost ignored by soil survey methodologies and soil classifications. The soil survey manual (Soil Survey Division Staff, 1993) classifies the urban soils under the undifferentiated areas. For a long time soil classification systems like the Soil Taxonomy (Soil Survey Staff, 1999), World Reference Base (WRB) for Soil Resources (FAO, 1988; 1998), and the Russian Soil Classification

System (Shishov et al., 2004) did not pay specific attention to urban soils. Only recently, the increasing importance of urban areas and recently grown interest to their soil resulted in enhancements of WRB allowing considering and diagnostic of urban and industrial soils, given as a new reference group of Technosols (FAO, 2007; Rossiter, 2007). The new edition of Russian soil classification is also expected to include taxons referring to urban soil types and subtypes (Prokofyeva et al., 2011). In the past decades, the demand for soil information changed from a qualitative description of soil types into a quantitative description of soil properties to be used in a range of modelling studies. There is an increasing call for spatially exhaustive soil information to deal with global issues like climate change, to study soil dynamics in natural and urban areas (Vrscaj et al., 2008; Dominati et al., 2010; Pickett et al., 2011).

Most insight into urban soil organic carbon (SOC) comes from local case studies that do not provide spatially exhaustive data (Jo and McPherson, 1995; Bandaranayke, 2003; Schneider and Woodcock, 2008). Conventional soil surveys (Turin, 1959; Gavriluk, 1963; Fridland, 1972; Soil Survey Staff, 1999) will provide insight in the spatial variation of soil types. The information is presented as qualitative data in the form of discrete maps. Soil property information can be derived from the maps by assuming that the observed soil properties in the representative soil profiles for the various soil types are a good representation of the mapping unit. Traditional soil surveying techniques are expensive as they require a large number of observations. In addition, the approach is not very suitable for an urban environment that is characterized by short distance variability with a lot of abrupt changes. Recently digital soil mapping (DSM) was developed (McBratney et al., 2000; 2003). DSM typically focuses on soil properties and aims to create continuous surfaces of these properties on the basis of a limited number of soil observations and quantitative, statistical relationships with auxiliary information. If the auxiliary information reflects the most important soil forming factors (e.g. digital elevation models representing topography), the methodology can give satisfactory results based on a limited number of field observations. Conceptually DSM provides good opportunities to describe the variability in SOC. However, there are some limitations for the assessment in urban areas. Very high short-distance variability within the urban areas and long distances between settlements limit the use of traditional interpolation techniques. DSM typically uses a range of explanatory variables like climate, topography and land-use (Dobrovolsky and Urussevskaya, 2004; Minasny et al., 2013) in a multiple regression approach (Kern, 1994; Ni, 2001; Wang et al., 2004). However, in the urban environment more attention is needed for anthropogenic soil forming factors. Finally, the urban environment may require specific attention to subsoil carbon in contrast to many regional and global analyses, where the estimation was focused on the top layer (Bui et al., 2009; Mishra et al., 2010; Martin et al., 2011).

An approach to analyze and map soil carbon in the urban areas and to assess its contribution to regional carbon stocks is lacking. Nevertheless, there is a strong demand for these assessments in urbanized regions. A good example is the Moscow Region, which is the most urbanized area in Russia with more than 10% of the territory occupied by settlements (Garankin et al., 2011). Urbanization in the Moscow Region continues at a rapid pace. In July 2012 the legal extent of Moscow city was enlarged 2.5 times, allowing for an extra 2500 km^2 to be converted into urban areas (http://www.mos.ru/en/about/borders). Up-to-date SOC maps for the area are lacking and up-scaling of existing, detailed SOC maps (Nilsson et al., 2000; Kudeyarov et al., 2007) is impossible due to the limited number of point data in urban areas.

The aim of the study is to adapt DSM techniques to map and assess carbon stocks in the urban environment while dealing with functional zoning, and the age and size of the settlements. The approach is implemented to map topsoil and subsoil SOC in the highly urbanized Moscow Region

4.2. Material and methods

The spatial distribution of topsoil and subsoil SOC in the region is analyzed using the basic concepts of DSM (McBratney et al., 2000; 2003). Following the classic Dokuchaev's concept of genetic soil science and soil forming factors, soil carbon stocks were described as a function of relief, parent material, climate, organisms (vegetation and land-use) and time (Kovda and Rozanov, 1988; Dobrovolsky and Urussevskaya, 2004). Given the specific conditions in the urban environment, additional anthropogenic factors, including soil sealing, functional zoning, size and age of the settlements were taken into account (Stroganova et al., 1997; Prokofieva and Stroganova., 2004; Lorenz and Lal, 2009). A stratified randomized sampling design was implemented with observation points located within and outside settlements in different parts of Moscow Region to represent traditional and urban specific soil forming factors. Topsoil and subsoil carbon stocks were calculated using soil carbon concentrations, soil depth, and soil carbon. In the urban areas also the ratio of sealed areas in settlements and anthropogenic inclusions were taken into considerations. Auxiliary data were derived from available sources and used as explanatory variables in general linear models. Three separate regression models were developed: i) a model focusing on the non-urban areas, ii) a similar model but including the urban areas, and iii) an urban specific model where urban-specific factors were also included (urban-specific model). In addition to mean SOC stocks, coefficient of variance values were mapped for the strata. The maps were validated based of an independent validation dataset.

4.2.1 Study area

Moscow Region measures 46,700 km^2. The territory of Moscow Region has a plain relief ranging from 100m above sea level in the East to 300m above sea level in the North and West. Climate of the region is temperate continental with mean annual temperatures of 5.8°C in Moscow city and ranging between 3.5°C to 5.8°C outside the city. Average annual rainfall varies from 780mm in the North to 520mm in the South. Parent material includes moraine loam and clay in the northern and central parts, fluvioglacial sands in the East, and cover loam in the South. Soils include Orthic Podzols in the North, Eutric Podzoluvisols in the center, Orthic Luvisols and Luvic Chernozems in the South, intrazonal Dystric Histosols in the eastern part of the region and Eutric Luvisols in the flood-plains of the Moskva and Oka rivers (Egorov et al, 1977; FAO, 1988; Shishov et al., 2004). Vegetation varies with climate and is represented by three bioclimatic zones: south-taiga, deciduous forests and steppe-forest (Shishov and Voitovich, 2002). Anthropogenic changed landscapes (agricultural, fallow, and urban lands) occupy nearly 60% of the territory. The urban area is rapidly expanding and currently occupies more than 10%, including 68 cities and towns with 18.8 million people (including Moscow city). Moscow is the largest city in Europe with a population of over 11.2 million people.

4.2.2 Available data

Although legacy SOC data for Moscow Region exists (Nilsson et al., 2000; Shishov and Voitovich, 2002; Romanenkov et al., 2007), it mostly focuses on agricultural and natural areas, it does not consider specific features of the urban environment, and only includes topsoil data. Following the DSM concept (McBratney et al., 2000) we assumed SOC stocks to be a function of the soil forming factors. Quite a few sources of auxiliary data representing different soil forming factors were available. In the urban areas, specific factors were added to represent the anthropogenic influence better. In coherence with the majority of regional studies, we linked carbon stocks to climate, relief and land use. The information was obtained from available global databases. Climate conditions were described by the 30 arc-second WorldClim database in terms of average annual temperature and total annual rainfall (Hijmans et al., 2005). Since the relatively plain relief of the study, area we used slope as an explanatory variable. Slope was derived from the 90m SRTM digital elevation model (Jarvis et al., 2008). The Land Cover Map for Northern Eurasia for 2000 (Bartalev et al., 2003) was used to describe differences in land cover. In addition, the normalized difference vegetation index (NDVI) was derived from a Landsat image for 2000 (30m resolution) describing differences in vegetation. Although parent material is an important factor for SOC prediction, detailed information on parent material was lacking. Therefore, the existing exploratory soil map of Moscow Region was used (Shishov and Voitovich, 2002). The general soil groups correspond well with different parent materials.

In the urban environment, settlement history is known to have a strong impact on urban SOC particularly in the subsoil (Lorenz and Lal, 2009; Vasenev et al., 2013c). Information on the size and age of settlements was obtained from official sources (RFSSS, 2012). However, the database only included the age of settlement and did not differentiate within the towns. Particularly in bigger cities like Moscow this was limitation. Spatial heterogeneity of SOC stocks in urban areas is influenced by the sub-division of cities in functional zones, which specify the different urban areas (i.e. industrial areas, courtyards, green zones etc.). However, any spatially explicit information on functional zones was lacking for the Moscow Region. Assuming that recreational, residential and industrial functional zones differ in the vegetation and percentage of sealed areas, we derived borders of functional zones based on the NDVI.

The final list of available data contained 1) traditional soil forming factors (elevation, climate, land-use, vegetation and soil) and 2) urban-specific soil forming factors (functional zoning, size and history of the settlements, including age and population density) (Table4.1).

Table 4.1 Characteristics of sampled settlements and Moscow city

Settlement	Coordinates (N/E)	Area (km^2)	Population (×1000)	Age category (settling year)	Soil type
Dubna	56°45'/ 37°09'	71.6	63	Young (1950)	Orthic Podzols
Sergiev Posad	51°18'/ 38°08'	50.4	105	Ancient (1300)	Eutric Podzoluvisols
Voskresensk	55°19'/ 38°41'	47.0	104	Old (1800)	Eutric Podzoluvisols
Shatura	55°34'/ 39°32'	33.0	33	Old (1500)	Dystric Histosols
Pushino	55°50'/ 37°37'	17.8	20	Recent (1970)	Orthic Luvisols
Ser. Prudi	54°27'/ 38°44'	3.7	9	Old (1600)	Luvic Chernozems
Moscow	55°45'/ 37°37'	1097.0	10 381	Ancient (1100)	Eutric Podzoluvisols

4.2.3 Sampling procedure

SOC stocks in Moscow Region were sampled in 2010-2011. Sampling was challenging due to the variability in environmental conditions within the region and the focus on the urban areas. DSM studies often sample at least 100 - 250 points to assess the relations between the auxiliary data and the target variable properly. Observation points could not be distributed randomly throughout Moscow Region. This would result in a small number of observations in the urban areas (covering only 10%). It was also not possible to include all 68 cities and towns into the sampling design. Therefore, we decided to implement a stratified sampling design. Sampling points were chosen in Moscow city and six settlements in the region in such a way that the different combinations of traditional and urban-specific factors distinguished above were represented (Table 4.1) (see Vasenev et al., 2013b for details on the sampling design). Samples were taken inside the settlements and from surrounding areas. Seven settlements with three surrounding land uses (arable land, pasture, and forest) and three functional zones (residential, recreational and industrial) were sampled which gave us a total of 244 locations (69 in Moscow city and 175 in its surroundings (95 from urban areas and 80 from non-urban sires)). The validation dataset was collected during the independent soil survey in 2012. It included samples from the Moscow city (12 points), urban and non-urban sites from Istra and Odintsovsky district located in the West of Moscow Region (8 and 2 points correspondingly), Serpuhovsky district located in the South of the region (11 points), Taldomsky district in the North of Moscow Region (4 points), Serebryano-Prudsky district on the South (4 points) and Shatursky district in the East (7 points). In total 26 urban and 24 non-urban sites were sampled for the validation dataset (Figure 4.1). Inside each stratum, sampling plots were selected randomly. For each plot, 5 topsoil (0-10cm) samples were taken from a 2 m^2 square plot (corners and center) and pooled into a single composite sample. A single sample was taken from the subsoil (10-150cm) at the center of the plot. The sampling design covered only the open areas, as no samples from sealed soils could be taken. All samples were air-dried and roots and plants fragments were removed. Subsequently, the samples were sieved (1mm) and pulverized using an agathic mortar. Afterwards SOC content in prepared soil samples was measured using the dichromate approach with spectrophotometric end point detection following Turin approach with Nikitin's modification (Vorobyova, 1998) with three replications.

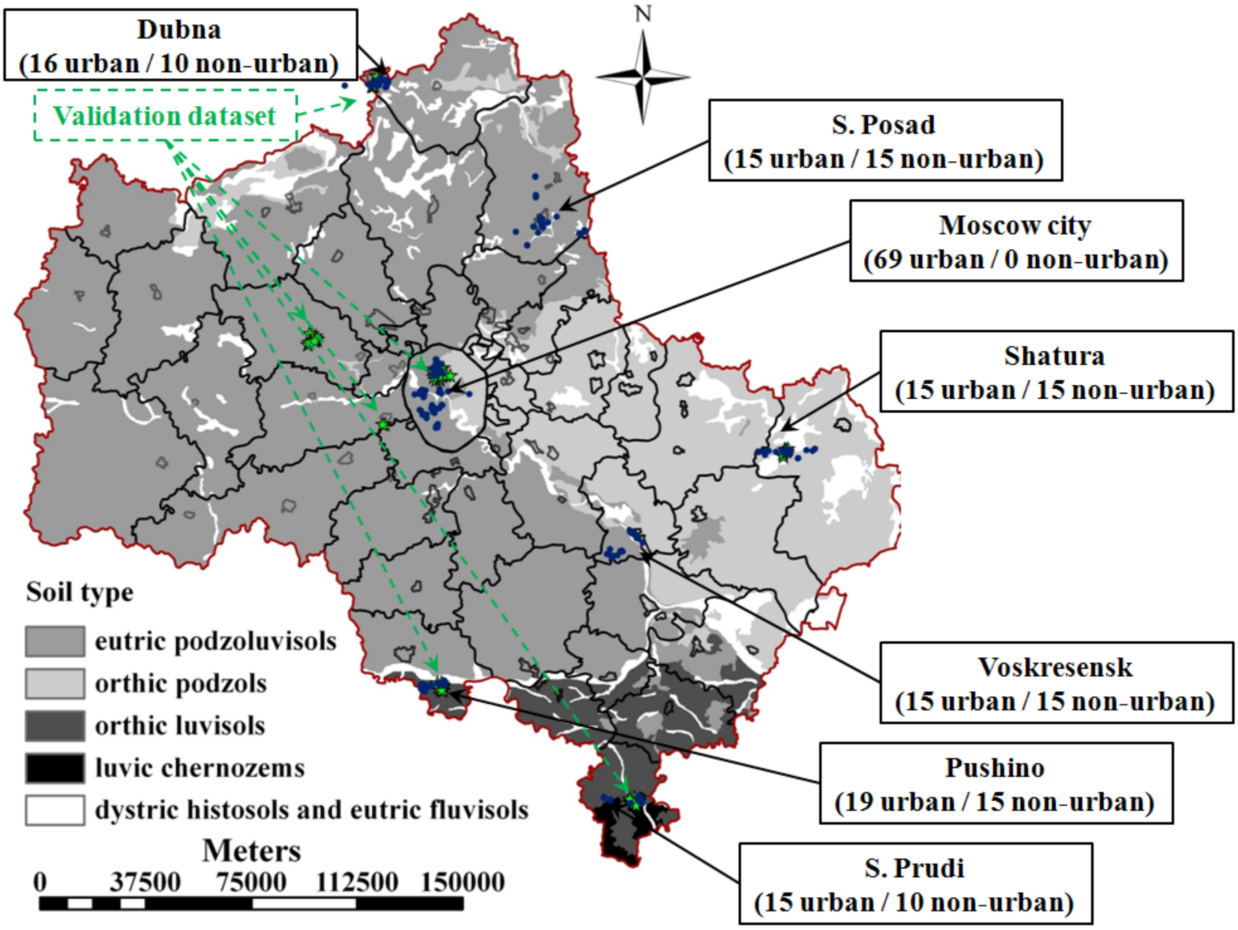


Figure 4.1 Location of urban and non-urban sampling points for mapping and validation in Moscow region

4.2.4 Auxiliary data processing

<u>Traditional factors</u>

The data on elevation, climate, land-use, vegetation and soil were processed to obtain explanatory variables describing the more traditional soil forming factors. From a variety of bio-climatic variables in the WorldClim database, mean annual temperature and annual precipitation were selected. Relief was represented by slope (degrees). The 27 land-use types from the land cover map were aggregated into five main categories: forest, natural pasture, bogs, arable land, and urban areas. The soil map described soil variation through 1289 delineated areas and 319 mapping units. Each of the mapping units is a homogeneous of complex mapping unit containing up to seven soil types and sub-types. In this study, 5 major soil groups were used that corresponded strongly to differences in parent material: i) orthic Podzols, ii) eutric Podzoluvisols, iii) dystric Histosols and eutric Luvisols, iv) orthic Luvisols, and v) luvic Chernozems. Soil variability has a considerable influence on the relevance of estimating and modelling of soil properties including carbon stocks (Fridland, 1972; Kiriushin and Ivanov, 2005). In order to consider soil variability the soil complexity index (S_{ci}) was derived as:

$$S_{ci} = N_{su} \times (S_{u2} / S_{u1}) \qquad (4.1)$$

Where N_{su} is the number of soil types in the mapping unit, S_{u1} the percentage of the predominant soil type within the mapping unit, and S_{u2} the percentage of the second dominating soil type. S_{ci} values varied from 0 (when only one soil unit is present) to 7 (when 7 soil units with equal percentage are present). All maps have been resampled to the resolution of the land cover map of 720 m.

Urban-specific factors

Settlements were classified considering their size and age. Four size categories (megapolis, large, middle size and small) and four age categories (ancient, old, young and recent) were distinguished. Due to its size, Moscow city was also subdivided into four natural landscape regions, based on the location with respect to the Moskva river: central, right-bank, left-bank and river-valley. Although considerable impact of functional zoning on soil features was reported (Prokofieva and Stroganova, 2004; Vasenev et al., 2012), no spatially explicit information on the distribution of industrial, residential and recreational zones was available. We used NDVI to derive the information on functional zoning. NDVI is widely used for the spatial analysis of land cover, however there is lack of knowledge how to use it to derive functional zones inside urban areas. In a preliminary analysis NDVI values were compared with the information on functional zones from the survey in urban areas (n=164). All observations of recreational areas had NDVI values below 0.12 whereas all industrial and recreational areas showed NDVI values above 0.12 (Figure 4.2). Although the NDVI in industrial areas exceeded the NDVI in the residential area, there was no significant separation that allowed for a classification on the basis of the NDVI. Therefore, we only considered the difference between two major functional zones: recreational and or residential/industrial. In total all the information on traditional and urban-specific factors influencing SOC was organized in 15 data layers (Table 4.2).

Table 4.2 Auxiliary data used for digital soil mapping in the Moscow region

Variable	Source
Traditional factors	
Mean annual temperature	Hijmans et al., 2005(www.worldclim.org)
Total annual precipitation	Hijmans et al., 2005(www.worldclim.org)
Bioclimatic zones	Shishov and Voinovich, 2002
Elevation	Jarvis et al., 2008 (srtm.csi.cgiar.org/index.asp)
NDVI	Landsat image (landsat.org)
Soil type	Shishov and Voinovich, 2002
Soil complexity index	Shishov and Voinovich, 2002 Soil of Moscow region…, 2002
Number of soil units per polygon	Shishov and Voinovich, 2002
Land-use type	Bartalev et al., 2003 (www.gvm.jrc.it/glc2000)
Urban-specific factors	
Functional zone	Landsat image (landsat.org)
Urban/ non-urban	Shishov and Voinovich, 2002
Moscow city/ Moscow region	Shishov and Voinovich, 2002
Size of the settlement	RFSSS, 2012
Age of the settlement	Official data from www.mosreg.ru
Landscape district of Moscow city	Ilina, 2000

4.2.5 Statistical analysis and modelling

Normality of the distribution of SOC values was checked by Shapiro-Wilk's W test and homogeneous of variances was checked by Levene's test. One-way ANOVA was used to check significance of difference in SOC between different groups (soil types, land-use types, cities of different age, size etc.). A statistical, multiple regression model correlated SOC contents to the explanatory variables to predict the topsoil and subsoil SOC contents in the area. Auxiliary information included both continuous and categorical data. Relationships between SOC contents and secondary data were analyzed using general linear models (GLMs). Categorical variables were introduced as dummy variables (equal 1 if a location was within a particular unit and 0 otherwise). The correlation between explanatory variables was analyzed in advance in order to prevent multicollenearity.

The main objective of the study was to analyze whether urban areas and urban-specific factors influence the results of regional SOC assessments. To show the effect different statistical models were developed in three consecutive steps:

Step 1: urban areas were excluded from the analysis and a model was developed only for the non-urban areas and considering the traditional factors (GLM1).
Step 2: urban areas were added to the analysis and a model was developed for the entire area and considering the traditional factors (GLM2)
Step 3: the total area was stratified into non-urban, urban (excluding Moscow city), and Moscow city. The model for the non-urban areas (GLM3n) was based on the traditional factors (see GLM1 above). The model for the urban areas (GLM3u) was estimated using traditional and urban-specific factors. The model for Moscow city (GLM3m) included the same factors as GLM3u plus the landscape regions in Moscow city.
All the above models were developed separately for the topsoil and the subsoil. The general linear models were obtained by a backward stepwise linear regression keeping the statistically significant variables ($p<0.05$). The predictive power of each statistical model was characterized by the coefficients of determination R^2 and R^2_{adj}. Statistical analysis was performed in STATISTICA 6.0 (Borovikov, 2003).

4.2.6 Mapping carbon stocks

Maps of SOC concentrations in the Moscow Region were developed using the GLMs. Separate maps were created for topsoil and subsoil. First map for only non-urban areas was derived using GLM 1. A second map for the entire region without stratification was derived using GLM2. A third map was derived where the area was stratified based on urbanization. The 3 models GLM3n,u,um were used to evaluate SOC stocks. Afterwards separate SOC maps for urban and non-urban areas of Moscow Region and SOC map for the Moscow city and other settlements in Moscow Region were created. All the maps based on traditional factors (GLM 1, GLM2 and GLM3n) had the resolution of 771m, since it was the lowest resolution among all explanatory variables. Urban-specific factors required a higher level of detail. Thus, the calculations for the urban areas were carried out at a resolution of 71m resolution and then aggregated to 771m. Many DSM studies include the use of regression kriging (McBratney et al., 2003; Hengl et al., 2007; Minasny et al., 2013). The residuals of the GLM are analyzed for spatial autocorrelation and, if present, the residuals are interpolated using kriging (Hengl et al., 2007). In this study, the clustered sampling resulted in large areas without sample locations inhibiting the interpolation of the residuals. Therefore, the maps of SOC contents on the basis of the regression models were used.

To convert the soil organic carbon contents into soil organic carbon stocks, it is necessary to take into consideration the depth of the soil profile, anthropogenic inclusions (no rocks or stones are found in the rural or natural areas), and the bulk density. Anthropogenic inclusions (bricks, concrete flags and service tubes) are present in the urban environment and we often faced them during our sampling campaign. To consider cut-off soil profiles, a correction coefficient (K_{si}) was included in the analysis. K_{si} was calculated based on the field profile descriptions and equation 2 considering the fraction of cut-off profiles (cases, where augering up to 150cm depth was not possible because of stoniness) for different functional zones.

$K_{si} = 1 + (N_{cp}/N_t) \times (D_{cp}/140 - 1)$ (4.2)

In which N_t - the total number of observation points per functional zone per settlement, N_{cp} number of plots with cut-off profiles per functional zone per settlement, and D_{cp} subsoil depth within the cut-off profiles. Conversion from SOC contents to SOC stocks was performed based on equations 3 and 4.

$SOC_{sp} = (SOC \times d \times K_{si} \times BD) / 10$ (4.3)

Where SOC_{sp} the specific soil organic carbon stock per area unit (kg/ m^2), SOC the soil organic carbon content (%), d the depth of the layer (cm), and BD the soil bulk density (g/cm^3).

$SOC_t = SOC_{sp} \times S \times P_{oa} \times 10^3$ (4.4)

Where SOC_t total soil organic carbon stock (Tg), P_{oa} percentage of the open (non-impervious) area, and S area (km^2).

The depth of the layer was 10cm (0-10cm) for the topsoil and 140cm (10-150cm) for the subsoil. Values for BD were taken from the literature and fixed for the combinations of land-use and soil types in Moscow Region (Shishov and Voitovich, 2002; Gerasimova et al., 2003), which resulted in BD ranges of 0.7-1.1 g/cm^3 for the topsoil and for 1.0-1.4 g/cm^3 for the subsoil (Table4.3). The percentage of open areas within settlements P_{oa} was assigned per functional zone 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 (Vasenev et al., 2013a). Finally, six maps of SOC stocks in Moscow Region with were developed, representing topsoil and subsoil stocks, including/ excluding urban areas and considering/ non-considering urban-specific factors. All GIS analysis was carried out in ArcGIS (Harder et al., 2011).

Table 4.3 Topsoil and subsoil bulk densities (g/cm³) for different soils and land cover classes in the Moscow region based on Shishov and Voinovich (2002) and Gerasimova et al. (2003)

Land-use / Soil	Cropland	Meadow	Forest	Bog	Urban
Eutric Podzoluvisols	1.2/1.4	1.0/1.2	0.9/1.3	0.7/1.0	1.1/1.3
Orthic Podzols	1.3/1.6	1.1/1.4	1.0/1.4	0.7/1.0	1.1/1.3
Dystric Histosols and Eutric Luvisols	1.2/1.4	1.0/1.4	1.0/1.4	0.7/1.0	1.1/1.3
Orthic Luvisols	1.2/1.4	1.0/1.3	1.0/1.3	0.7/1.0	1.1/1.3
Luvic Chernozems	1.2/1/3	1.0/1.2	1.0/1.2	0.7/1.0	1.1/1.3

4.2.7 Analysis of variability

For many applications the average carbon stocks and its variability in a certain strata are more essential than the exact value at a specific location. Therefore, the primary results of the carbon stocks were also aggregated to the different strata, representing different combinations of distinguished traditional and urban-specific factors. The average carbon stocks and standard deviation (SD) and coefficient of variances (CV) of the carbon stock within the strata were calculated.

4.2.8 Validation

The resulting maps were evaluated by validation with an independent dataset of 50 points collected during a survey in 2012.. The validation of the non-urban SOC map, based on GLM1 was limited by 24 points, whereas conventional (based on GLM2) and urban-specific (based on GLM3n,u,m) were validated by all 50 points. The difference between observed and predicted values was described by the Mean Error (ME),, Pearson correlation coefficient (r) and the coefficient of determination R^2, and by mean square deviation (MSD) and its components: squared bias (SB), nonunity slope (NU) and lack of correlation (LC) (Gaugh et al., 2003).

4.3. Results

4.3.1 Descriptive statistics

The analyses showed an average SOC concentration of 4.4% in the topsoil and 2.3% in the subsoil. The variability in SOC was high with CVs of 48% for the topsoil and 60% for the subsoil. SOC contents in the topsoil did not differ significantly between urban and non-urban areas but SOC content in the subsoil was significantly higher in urban areas ($p < 0.05$). SOC contents differed between the various land-use and soil types. The highest topsoil SOC contents were found in recreational (average=5.1%, SD=2.4%) and industrial areas (average=4.5%, SD=2.2%) respectively, whereas the lowest values were found under pasture (average 3.6%, SD=2.1%). The same tendency was found in the subsoil. The highest SOC contents in the topsoil were found in the Dystric Histosols (average =5.5%, SD=2.3%) and Orthic Podzols (average=5.0%, SD=2.8%). The highest subsoil SOC was found in the urban Technosols (average= 2.4%, SD=1.5%) where concentrations were significantly higher than in any other land-use type.

4.3.2 General linear model for SOC

In order to analyze the effect of urban areas and urban-specific factors on the regional assessment of carbon stocks 8 separate linear models were developed (Table 4.4). The models included 6 to 10 explanatory variables. The explained variance of SOC varied from 13-16% for GLM2 to 18-31% for the other models.

Table 4.4 Explanatory variables (+: included; - excluded) and determination coefficients of alternative general linear models describing SOC contents in topsoil and subsoil for Moscow region

GLM/ layer*	Explanatory variables**											R^2	R^2_{adj}
	NDVI	slope	mat	prec	sci	lu	st	fzag	ts	ta	Dist		
1/top	+	+	+	+	-	+	+	-	-	-	-	0.31	0.22
1/sub	+	+	+	+	+	+	+	-	-	-	-	0.23	0.12
2/top	+	+	+	+	-	+	+	-	-	-	-	0.13	0.08
2/sub	+	+	+	+	+	+	+	-	-	-	-	0.16	0.11
3u/top	+	+	+	+	+	-	+	+	+	+	-	0.18	0.09
3u/sub	+	+	+	+	+	-	+	+	-	+	-	0.18	0.10
3um/top	+	+	-	-	+	-	+	+	+	+	+	0.31	0.20
3um/sub	+	+	+	-	+	-	+	+	+	+	+	0.27	0.15

4.3.3 Mapping SOC stocks

Carbon stocks in the region were estimated and mapped on the basis of the formulas 2-4. At the first stage the K_{si} coefficient was estimated based on the number of cut-off profiles in different functional zones of the settlements observed (Table 4.5). The mean K_{si} for industrial areas was significantly lower than ones for residential and recreational. However, with the NDVI images we could only separate the recreational areas Therefore a single K_{si} was calculated for industrial and residential areas (0.77) and a separate K_{si} was calculated for the recreational areas (0.85). In the non-urban areas no cut-off profiles were found and a K_{si} of 1.00 was used.

Table 4.5 Values for soil variability (K_{si}) for different settlements and functional zones in Moscow region

Settlement	Industrial				Residential				Recreational			
	N_t	N_{cp}	D_{cp}	K_{si}	N_t	N_{cp}	D_{cp}	K_{si}	N_t	N_{cp}	D_{cp}	K_{si}
Moscow	22	14	60	0.64	25	2	85	0.97	22	6	60	0.84
Dubna	6	4	58	0.61	5	2	60	0.77	5	0	140	1.00
S. Prudi	4	1	90	0.91	6	1	10	0.85	5	2	65	0.79
S.Posad	5	3	27	0.52	5	2	30	0.69	5	1	20	0.83
Shatura	5	2	55	0.76	5	1	110	0.96	5	1	110	0.96
Pushino	5	2	30	0.69	9	1	90	0.96	5	3	40	0.57
Voskresensk	5	4	40	0.43	5	2	45	0.73	5	1	80	0.91
Mean				0.65				0.84				0.85

Afterwards the GLMs were implemented to create topsoil and subsoil SOC maps. Three maps were created using 1) GLM1, 2) GLM2, and 3) a combination of GLM3n, GLM3u, GLM3m (Figure 4.3).

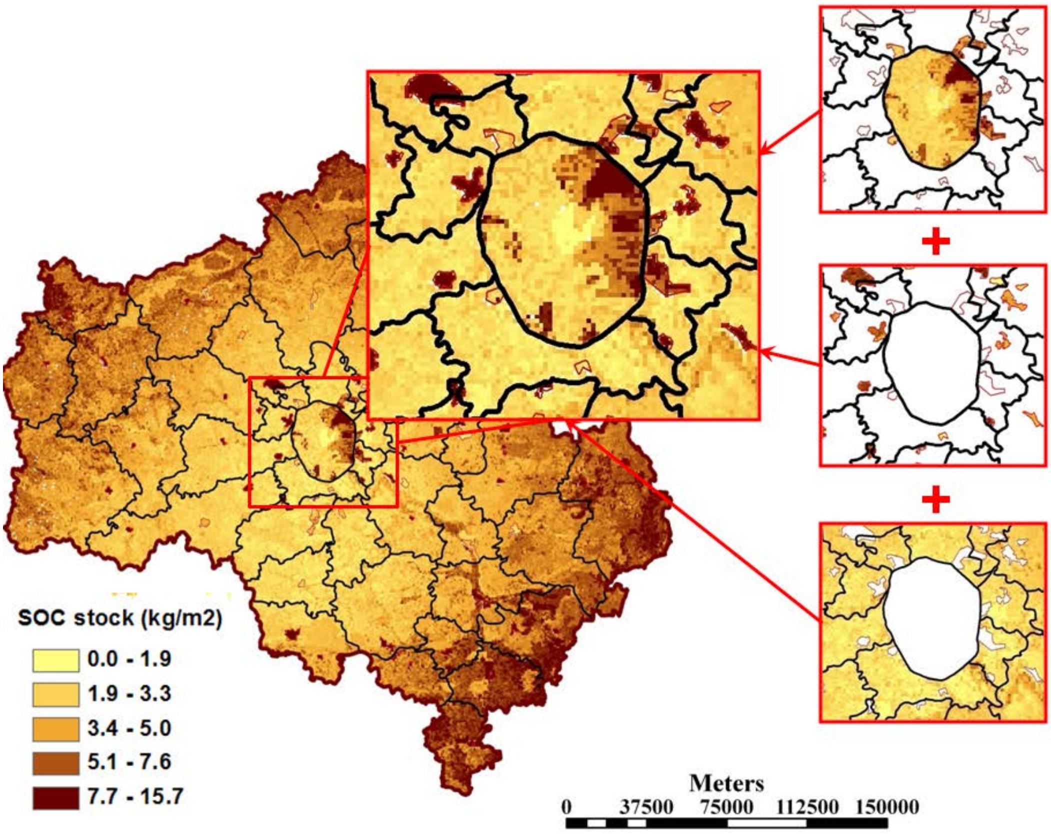


Figure 4.3 Development of the final urban-specific topsoil SOC map for the Moscow Region

Spatial patterns of carbon stocks distribution captured by the non-urban map demonstrated a strong coherence with the soil types dominating in the region. Areas with the highest topsoil and subsoil stocks are located in the South where Orthic Luvisols and Luvic Chernozems are found. The predominant effect of the soil type was well characterized by in the West of

Moscow Region where Orthic Podzols, Eutric Podzoluvisols and Dystric Histosols are found. Areas with large carbon stocks in the topsoil but also with a high spatial variability was typical for this area on the non-urban carbon map, although for the subsoil this area was much more homogeneous and characterized by low stocks (Figure 4.4 A, B). This difference between topsoil and subsoil stocks corresponds well with the typical profile distribution of Orthic Podzols and Eutric Podzoluvisols in the region (Shishov and Voitovich, 2002).Inclusion of the urban areas into the analysis altered considerably the spatial patterns of the carbon stocks. In addition, the largest stocks on the conventional map referred to the territory of Moscow city. This pattern was specifically clear for the topsoil whereas subsoil stocks were much more heterogeneous. When the urban areas were included into the analysis, average carbon stocks increased almost two times, while the coefficient of variance became lower (Figure 4.4 C, D). The highest spatial variability was captured by urban-specific maps. “Hotspots” of large topsoil and subsoil carbon stocks are the urban areas and nearest suburbs (Figure 4.4 E, F).

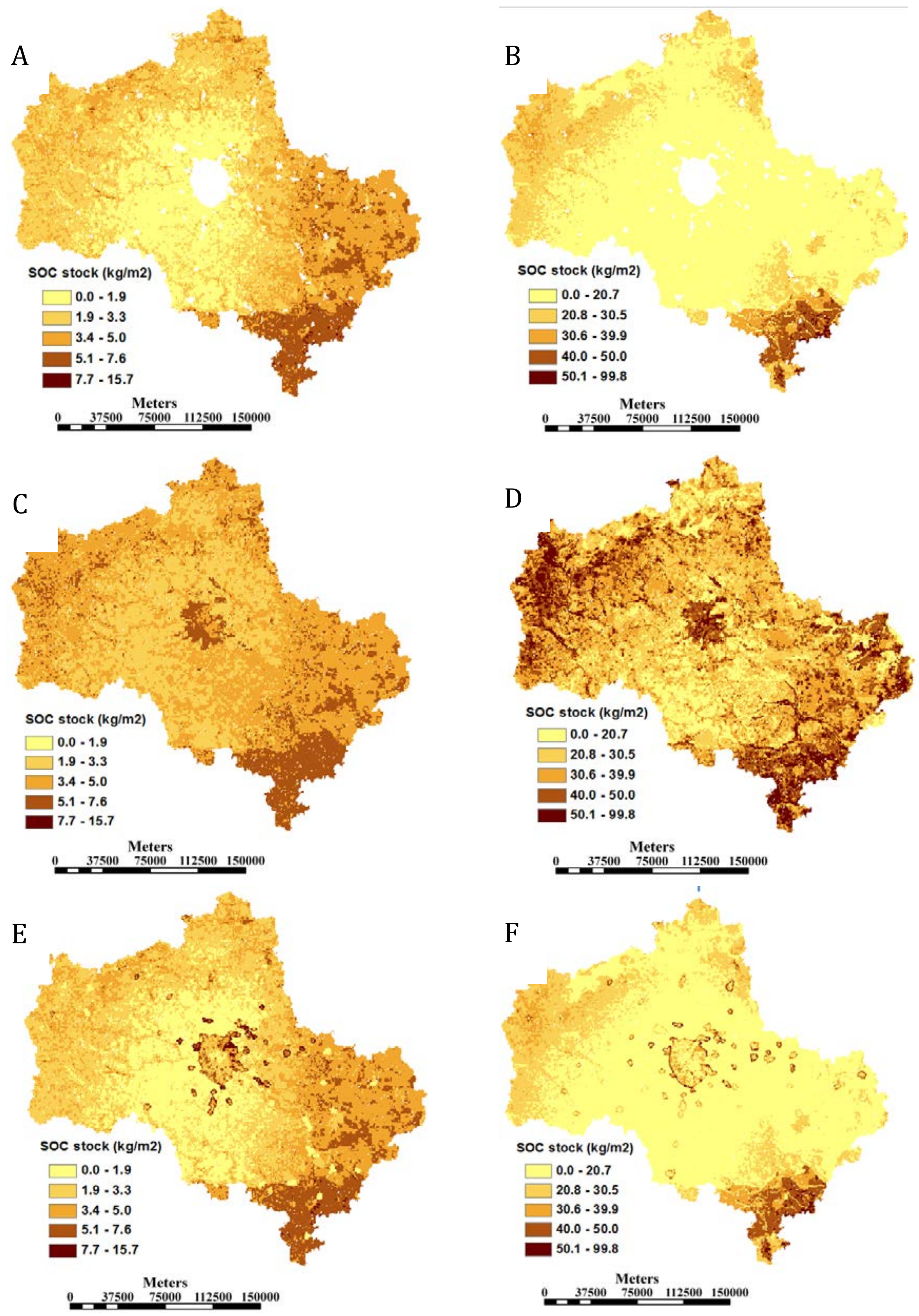


Figure 4.4. Topsoil and subsoil SOC stock maps, based obtained when urban areas are excluded from the analysis (A, B); when urban areas are included, but only tradition factors are considered (C, D) and when urban areas are included and both traditional and urban-specific factors are considered (E, F).

4.3.4 Analysis of the carbon stocks in Moscow Region

Based on non-urban, traditional and urban-specific maps we analyzed carbon stocks for the whole region and for specific strata. When urban areas are excluded (as is often done in global and regional studies), the total regional soil carbon stock was 783 Tg (SD=506 Tg) with 133 Tg (SD = 65 Tg) in the top 10cm and 650 Tg (SD = 502 Tg) stored in the subsoil. The average carbon stock for the region was 17.6 Gg/km^2 (SD = 11.4 Gg/km^2). The highest carbon stocks were found for the Orthic Luvisols and Luvic Chernozems.

Considerable differences in carbon stocks were found between land use types. Stocks on arable lands and meadows were the largest whereas the stocks in bogs and forests were 30-40% lower. Inclusion of urban areas into the analysis resulted in a large increase of the total carbon stock up to 1772 Tg (SD = 532 Tg), 90% of which was stored in the subsoil. The area-specific carbon stocks also doubled to 37.4 Gg/km^2 (SD = 11.5 Gg/km^2). Interestingly, such a considerable increase was not caused directly by total carbon stocks in the urban areas, but also through changes in the estimation of the GLM, which resulted in doubling of the specific carbon stocks for most of the soil and land-use types. The traditional approach based on GLM2 extrapolated relatively high SOC values measured in urban samples to the entire area of the region, non-considering urban-specific factors, like functional zoning, soil sealing and cut-off profiles and resulted in considerable overestimation. The urban-specific map, which considered all these factors, resulted in total carbon stock of 858Tg (80% stored in the subsoil) and specific stocks amounted to 18.8 Gg/km^2 (SD=11.8 Gg/km^2) (Table 4.6).

Table 4.6. Estimation and validation results for non-urban, conventional and urban-specific maps of topsoil and subsoil carbon stocks in Moscow region

	Non-urban		Conventional		Urban-specific	
	topsoil	subsoil	topsoil	subsoil	topsoil	subsoil
Estimation results						
Mean total C stock (Tg)	133	650	180	1542	142	716
SD of total C stock (Tg)	65	502	43	530	74	540
Mean specific C stock (Gg/km^2)	3.0	14.7	3.9	33.5	3.1	15.6
SD of specific C stock (Gg/km^2)	1.5	11.3	0.9	11.5	1.6	11.7
Validation results						
ME	1.00	4.40	2.04	27.75	0.56	6.03
r	0.49	0.48	0.46	0.22	0.47	0.50
R^2	0.24	0.23	0.21	0.05	0.21	0.3
MSD	4.02	120.64	6.12	962.91	3.89	127.13
b	0.57	0.6	0.91	0.16	0.37	0.46
SB	1.00	19.33	4.15	770.19	0.32	85.77
NU	2.38	77.44	0.11	161.69	3.57	80.39
LC	1.98	60.80	2.01	79.46	1.99	62.58

The urban-specific map allowed for a comparison of different non-urban land-use types and urban functional zones into the regional carbon stocks. Urban areas possessed the highest specific topsoil and subsoil stocks in comparison to all the other land-use types. The standard deviation was also larger than in the other sites (except to extremely variable subsoil stocks in bog areas). No significant influence of the settlement size on carbon stocks (one-way ANOVA, $p<0.05$) was found, whereas settlements of different age varied in SOC stocks considerably. Largest topsoil SOC stocks were found in the young towns (50-100 years old). Subsoil carbon stocks in ancient and young settlements were higher than for the others. Functional zoning demonstrated the most significant influence on carbon stocks in comparison to any other urban-specific factor. The amount of carbon stored in the topsoil and subsoil of the recreational areas was almost three times higher than in industrial and residential areas (Figure 4.5). This reaffirms the importance of the green space in urban areas for carbon storage.

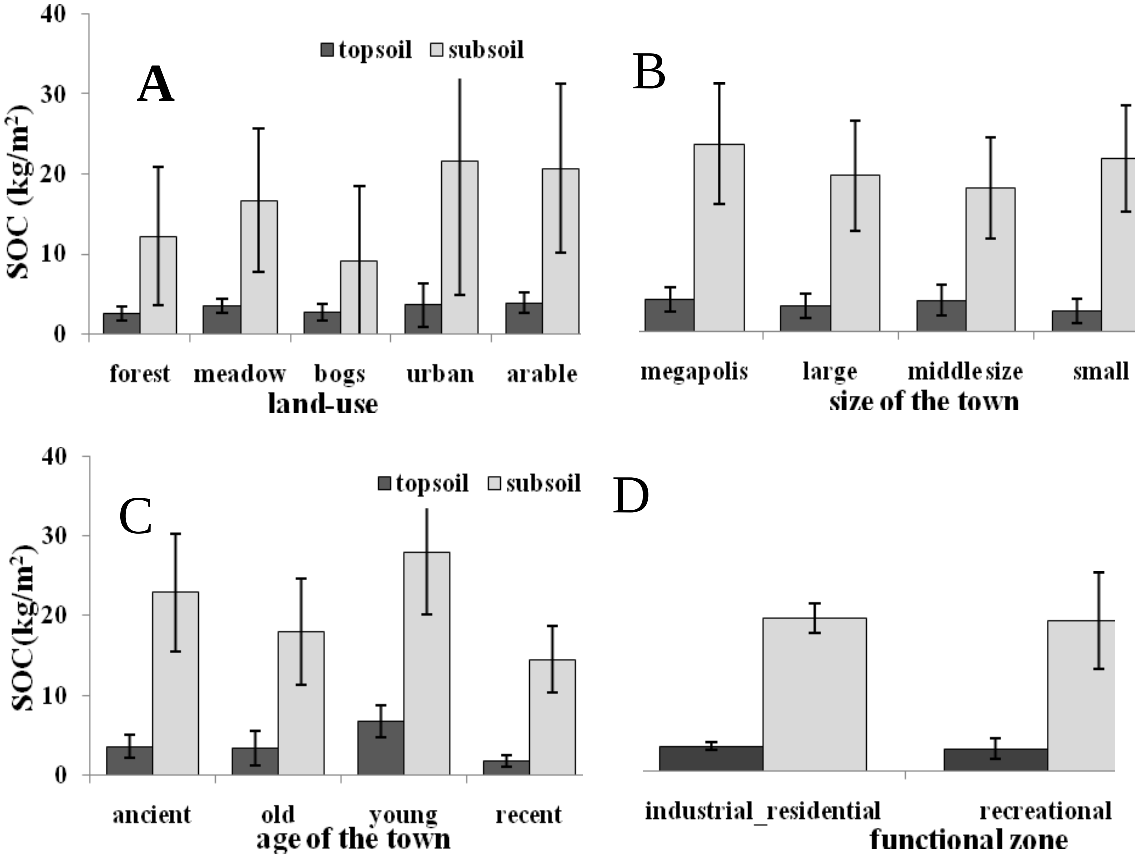


Figure 4.5 Topsoil and subsoil specific carbon stocks in different land-use types (A), in the settlements of different size (B) and age (C) and different functional zones (D)

4.3.5 Analysis of the spatial variability of SOC stocks

The maps show a high spatial variability in topsoil and subsoil carbon stocks in the region. The urban-specific maps showed the highest variation with an average CV almost double the one in traditional maps. Areas with the highest CV in the topsoil corresponded well with the settlement boundaries. However, for the subsoil the opposite pattern was found – urban areas were more homogeneous whereas the highest CV was obtained for the natural sites under orthic Podzols and eutric Podzoluvisols. Patterns of spatial variability shown by the non-urban map were similar for topsoil and subsoils with the highest CV values in the areas of eutric Podzoluvisols and the lowest shown for orthic Luvisols and luvic Chernozems. The exception was the area in the East covered by dystric Histosols where relatively homogeneous topsoil stocks (CV = 25-20%) were found in combination with variable subsoils (CV = 85-90%). Average CV values obtained from non-urban maps were 10-15% less than ones, derived from urban-specific maps. The conventional map demonstrated the lowest spatial variability with an average CV around 20-30%. Spatial variability patterns of the subsoil carbon stocks well corresponded to the zonal soil types with the highest topsoil CV shown for eutric Podzoluvisols and the lowest ones found in the orthic Luvisols areas. The settlement boundaries were not very clear except for Moscow city, where subsoil CV values were lower than in its surrounding. Almost no significant variability was shown for the topsoil carbon stocks, derived from the traditional map (4.6).

4.3.6 Validation of SOC maps

The maps obtained were validated by an independent dataset. Carbon stocks in the dataset were estimated following the same steps (formulas 4.3 and 4.4) as for the primary data. In all three maps the mean modelled carbon stocks were overestimated. This could be the result of incomplete consideration of urban-specific factors (soil sealing and cut-off profiles), decreasing the actual stocks found by the models. This is illustrated by comparison of ME for different models. Conventional model neglecting urban-specific factors showed the highest ME, which was 50% and 3 times higher than ones from non-urban and urban specific models for the topsoil and subsoil stocks respectively. Apparently, even urban-specific model could not consider all the factors, decreasing actual carbon stocks, although in comparison to other models it showed the lowest errors especially for the topsoil (Table 4.6). For the topsoil stocks, all three maps demonstrated similar correlation with the validation results. As for the subsoil stocks, the best correlation and determination coefficient was obtained for the urban-specific map. No significant correlation between subsoil stocks from the validation dataset and ones derived from the traditional map was found ($p<0.05$).

The highest MSD, and SB and LC was shown for the conventional model both for the topsoil and for the subsoil, although non-urban presented a lower MSD. Based on the MSD and its components urban-specific model performed better that non-urban model for the stock prediction of topsoil carbon stock, although for the subsoil stocks the performance of both models was comparable (Table 4.6).

4.4. Discussion

4.4.1 SOC contents and carbon stocks in Moscow Region

The different models showed large differences in the description of the soil carbon stocks in Moscow Region. Only a few carbon assessments are available for Moscow Region. Most of the previous analysis were focused only on forests and croplands (e.g. Isaev and Korovin, 1995; Romanenkov et al., 2007; Smith et al., 2007) and were performed either at the country scale or for the entire European part of Russia. The most recent assessment of SOC stocks by Nilsson resulted in 297.5 Pg carbon for the whole country corresponding to a specific stock of 17.3 Gg/km^2. This corresponded well with the specific stocks obtained from non-urban and urban-specific maps, although the results derived from the conventional map were almost double. IPCC reported 8.5 Gg C/km^2 in the top 30cm layer of taiga and south-taiga soils (IPCC, 2001), which is also comparable with our results when extrapolated to 150cm. However, linear extrapolation of topsoil SOC to the whole soil profile provides very rough estimations (Minasny et al., 2013; Kempen et al., 2011)

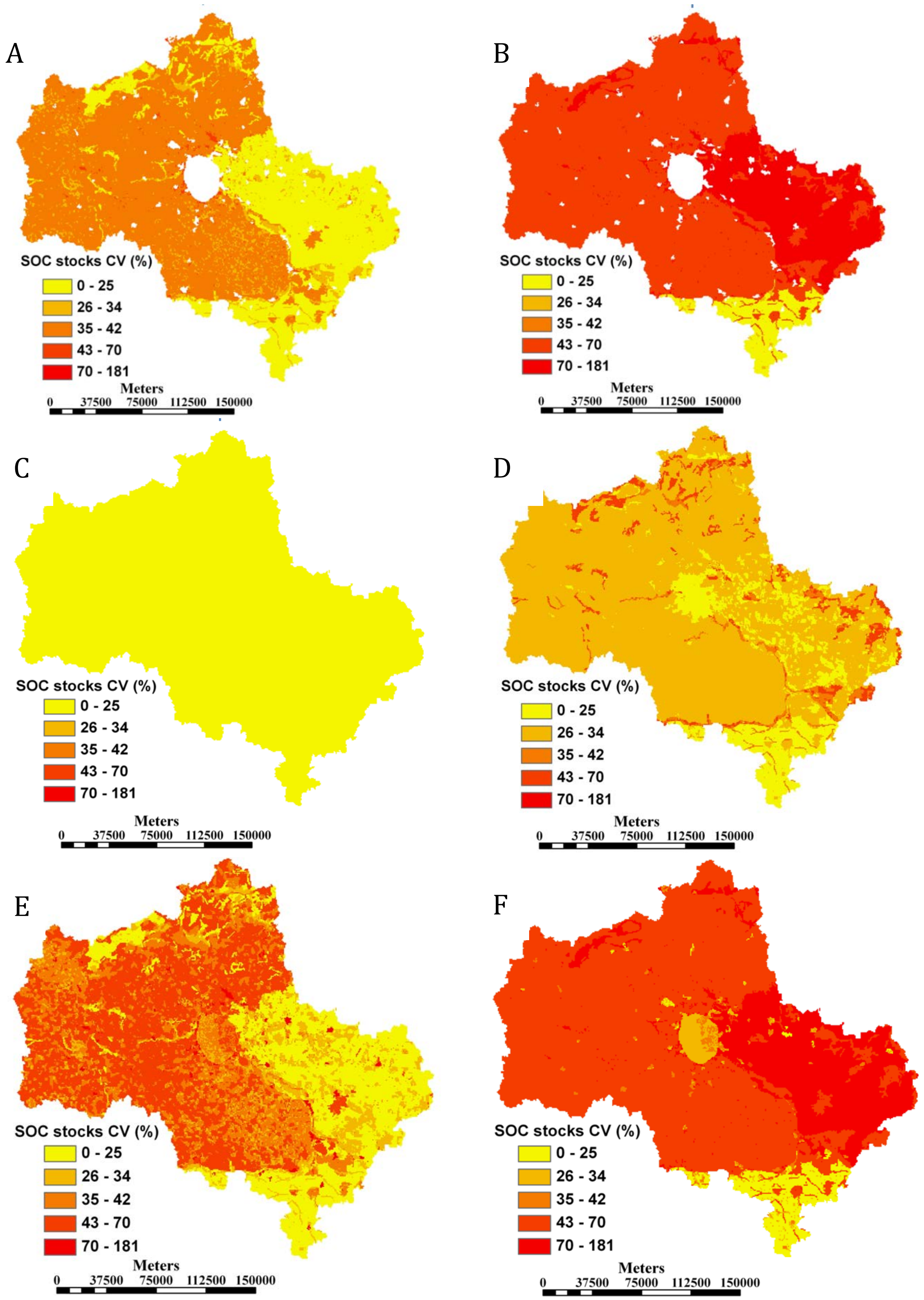


Figure 4.6. Topsoil and subsoil CV (%) values, derived from non-urban (A, B), traditional (C, D) and urban-specific maps

Although it is difficult to assess the relevance of the absolute values obtained, we compared the relative spatial patterns in carbon stocks shown by us with ones published in literature and found similar trends. We obtained maximal carbon stocks and contents in the region for Orthic Luvisols and Luvic Chernozems, which well corresponded with previous results (Orlov, 1998; Ananyeva et al., 2008). However, the high topsoil carbon content in the Orthic Podzols was unexpected according to the literature data (Shishov and Voitovich, 2002; Dobrovolsky and Urussevskaya, 2004). It may be explained by the incorporation of rich in organic matter Dystric Histosols into this category (Vasenev et al., 2013c). We demonstrated higher carbon stocks in croplands in comparison to forest areas, which is confirmed by the results obtained for the local areas in the Moscow Region before (Larionova et al., 1998; Kurganova et al., 2003). The highest topsoil carbon stock among all land-use types was shown for the urban areas. This was never reported for Moscow Region before but corresponds well with similar analyses in USA (e.g. Kaye et al., 2005; Pouyat et al., 2006). It was not possible to evaluate our subsoil stocks' results, as far as the majority of the existing assessments focused on the top layers.

4.4.2 Topsoil and subsoil carbon stocks

The main focus on the topsoil in most of current soil carbon assessments is based on the concept that the major part of SOC is accumulated in the top 30cm (IPCC, 2001; Minasny et al., 2013). This assumption is generally correct although there are quite a few studies for agricultural, urban and even some natural soils, showing carbon depth profile distribution, different from the assumed gradual decrease with depth (Lorenz and Lal, 2009; Kempen et al., 2011). The subsoil SOC content in the Moscow Region was, on average, half of the top layer, although subsoil were responsible for almost 90% of the total carbon stock. The ratio between topsoil and subsoil SOC was similar for different soil types except for Eutric Podzols where subsoil SOC amounted for only 36% of the topsoil value, which corresponded with the classical assumption on the Podzol profile (Egorov et al., 1977; Dobrovolsky and Urussevskaya, 2004). The contribution of the subsoil to total carbon stocks shown by the non-urban map was similar for different land-use types and amounted to 80%. Urban subsoil carbon stock predicted by urban-specific model was higher than for any other land-use type and amounted to 90% of the total stock.

4.4.3 Uncertainty of the estimated carbon stocks

Obtained absolute values of carbon stocks were rather uncertain, which was clearly shown by high CV values up to 70% and rather low R^2 of the GLM, referring to their quite poor performance. Such a high level of uncertainty could have been expected and rooted in high heterogeneity of the research area and quite a few assumptions made at different steps of modelling and estimation processes. High complexity of the bioclimatic conditions and land-use structure in Moscow Region (further complicated by our aim to analyze urban-specific factors with appropriate explicitness) and lack of available legacy data constrained us to use stratified sampling design. The majority of sampling points were concentrated in the urban areas, covering approximately 10% of total research area, thus considerable parts of the region were under-observed. Another source of uncertainty refers to the lack of explanatory data with a high enough resolution to analyze urban areas. For instance, we had to combine industrial and residential areas in one group and assume for them a similar soil sealing and cut-off profile percentage, although the field data showed significant differences between them. Including urban-specific factors into analysis resulted in quite a few assumptions. For example, the age was taken as a constant for the whole settlement; however, in reality the central parts of the towns are usually older than the suburbs. This could make especially high impact on the carbon stocks estimated for Moscow city, because of its extent and long history. All these factors resulted in large differences with the validation data. However, we believe that even with this level of uncertainty the obtained results were relevant since they clearly showed the considerable impact of the urban areas into regional carbon stocks and especially in their spatial distribution.

4.4.4 Mapping spatial distribution of carbon stocks

Depending on the research goal, information required from the regional carbon assessment may differ. When analyzing urban areas with extremely high heterogeneity, which is almost impossible to describe by regional analysis, understanding of the SOC stocks' spatial variability becomes much more valuable than traditional data on mean carbon stocks. The maps of carbon stocks' spatial variability based on CV values, aggregated for different soil types, land-use classes and for the urban areas of different size, age and functional zoning, provided essential information on the patterns behind spatial distribution of carbon stocks in the Moscow Region. High variation in the eastern part of the region can be explained by variable complexes of Dystric Histosols and Eutric Podzoluvisols in this area (Shishov and

Voitovich, 2002). Low variation was shown in the South with relatively homogeneous Orthic Luvisols and Luvic Chernozems. Inclusion of the urban-specific factor into analysis resulted in considerable increase of variation, obtained from urban-specific maps in comparison to conventional one, with the “hot-spots” strongly related to the settlement boundaries. This corresponds well with the assumption of high heterogeneity of urban areas (Gerasimova et al., 2003; Lorenz and Lal, 2009; Vasenev et al., 2013c) and illustrates the contribution of urban areas into spatial variability of the regional carbon stocks.

4.4.5 Comparing performance of the non-urban, conventional and urban-specific models

The main research question was to assess the importance of urban soils in regional carbon stock The comparative analysis of non-urban, conventional and urban-specific models vividly proved that several steps of the DSM adaption to urban condition were necessary. Inclusion of the urban areas into the analysis while excluding urban-specific factors resulted in a decrease of the predictive power of the model (<15% of total variance). Urban-specific models explained up to 30% of total carbon stocks’ variance, which was a considerable improvement in comparison to conventional model. The predictive power of the urban-specific model of the subsoil SOC stocks was 20% higher than one for non-urban model, whereas for the topsoil results both models were comparable. The validation with the independent dataset and further analysis with nine assessments (see Table 4.6) also proved the poorest performance of the conventional model in comparison to the others. The urban-specific and non-urban models were comparable in predicting subsoil carbon stocks although for the topsoil stocks urban-specific model performed better. Thus, we can assume that spatial variability and mean values of the carbon stocks in Moscow Region represented by urban-specific map reflected the real situation better than if specific of urban environment was not considered.

4.4.6 The influence of urbanization on soil carbon stocks

One of the main assumptions of the research was the important role of urban soils in carbon storage and their considerable contribution to the regional carbon stocks. The assumption was based on literature data (Qian et al., 2002; Lorenz and Lal, 2009; Zircle et al, 2011; Vasenev et al., 2013a) proving higher SOC contents in urban soils compared to non-urban ones. The prevalence of urban SOC was mainly significant for the subsoil due to the “cultural layers” in the urban soils (He et al., 2009; Dolgikh and Alexandrovskiy, 2010). Considering the deep subsoil, we expected to obtain larger urban carbon stocks than non-urban stocks. However, including the urban areas in the analysis surpassed our expectations. Total carbon stocks based on the map including urban areas were considerably larger than one excluding them, with 90% of all carbon stored in the subsoil. The analysis of the specific carbon stocks in different land-use types showed a significant rise of all of them, when new GLM equations, including field data from urban areas, was used.

One should be critical considering such a dramatic effect of urban areas on the regional carbon stocks. Apparently, this could be the result of the direct interpolation of relatively high carbon stocks observed in urban areas for the entire region. However, in addition to high average SOC stocks urban environment brings a number of specific features, including functional zoning, soil sealing and cut-off profiles. Ignoring of these factors can result in significant overestimation of average carbon stocks and underestimation of their spatial variability. This was clearly shown by the results, derived from urban-specific map. Average stocks obtained from this model were considerably lower and spatial variability – almost two times higher than ones, predicted by conventional maps. In comparison to non-urban map both SOC stocks and their variation were 10-15% higher. Considering that validation also proved the best performance of urban-specific model in comparison to others, we can assume that 10-15% increase of stocks and variability was an actual contribution of urban soils to the regional carbon stocks.

4.5. Conclusion

Mapping carbon stocks in a highly urbanized region is challenging due to the specific characteristics of the urban environment. As a result, each step of modelling and mapping should change. We implemented several models different in considering the urbanization impact: from total neglecting to incorporation of the specific factors within urban areas. In contrast to the majority of global and region assessments (i.e., Nilsson et al., 2000; Schulp and Verburg, 2009) we demonstrated that urban carbon stocks can be comparable or higher than those in natural areas and croplands. We also showed the considerable contribution of urban areas in total regional carbon stocks and their spatial variability. Moreover, the level of contribution differed for the implemented models, depending on the explicitness of incorporation of urban areas and factors. Consideration of urban areas and urban-specific factors resulted in a 10-15% increase of total carbon stocks and their spatial variability and a considerable improvement in model performance in comparison to the models that partly or totally ignore urban areas.

Our study proved the importance of urban areas in carbon storage, although the actual values of the carbon stocks remains uncertain. Part of this uncertainty may be avoided by increasing the number of sampling points and improving the quality of auxiliary data. However, considerable improvement requires much better understanding, further analysis and quantification of factors and processes of the urban environment. Predicting spatial variability of carbon stocks per strata of interest rather than estimating actual carbon stocks per specific location, as it was shown in our study, may also be a promising solution for regional studies.

Urbanization is among the most impetuous current land-use change trends, resulting in permanently increasing role of urban ecosystems in regional and global environment. Currently assessments of regional carbon stocks include significant uncertainty (Jobbagy and Jackson, 2000; Lal, 2004; Stockman et al., 2013). The developed approach to map soil organic carbon in highly urbanized region can enhance our understanding of regional carbon stocks and their spatial distribution, which is essential with the continuing urban sprawl around the world.

Acknowledgements

The project was partly supported by Governmental Grant # 11.G34.31.0079 and the Wageningen University Sandwich PhD Fellowship Program. The authors thank Julia Sotnikova, Dmitry Sarzhanov and Pavel Lakeev for the assistance with soil sampling and chemical analysis and Rik Leemans and Nadezhda Ananyeva for valuable suggestions and useful comments.

5 ANALYZING SPATIAL VARIABILITY OF SOIL RESPIRATION BY DIRECT AND INDIRECT METHODS

ABSTRACT

Soil respiration (Rs) is a major carbon outflow from soil to the atmosphere and an important indicator of in soil carbon stocks' temporal dynamics. Analyzing Rs is constrained by its highly variable in space and time. Both direct and indirect approaches can be used to capture this variability. Direct in situ measurements are more provide more accurate data on absolute CO_2 efflux and its temporal dynamics. However high labor intensity of repeated direct measurements limits number of observation points, which can be critical for analyzing spatial variability. Indirect measurements are less robust but enable measurements in considerable larger areas, and this is very important to analyze Rs in such a heterogeneous areas as urban areas. We analyzed in 2013 and 2014 Rs temporal and spatial variability at a 10 km^2 test area in Moscow city, which included adjacent forests, croplands and urban lawn plots. We also included Rs diurnal dynamics from July 2013. Similar diurnal and seasonal trends were found for all the investigated sites: Rs dynamics were mainly driven by soil temperature. The highest daily Rs was obtained between 7AM and 1PM. Rs during the growing season (June-October) was substantially higher than in other periods. Average Rs for the urban lawns was significantly higher than at the forest and cropland sites, although its spatial variability was high. We analyzed Rs' spatial variability at the test area during the growing season (June-October 2013, 10 time repetitions per point) by both direct and indirect approaches. Rs was monitored by *in situ* chamber approach with an IR Li-820 gas analyzer at 50 points. At the same area, 32 locations were sampled nearby the chamber collars and basal respiration (BR) was measured under controlled conditions. Rs was affected by anthropogenic disturbance with the highest values in urban lawns. BR was mainly controlled by soil organic carbon (SOC) with maximum rates in the forested area. Total variability by direct observations was 10% higher, than for BR, although the spatial variability captured by both approaches was similar. This was confirmed by a significant correlation between variance coefficients (CV) of the values. This shows that BR is a relevant proxy to analyze the spatial variability of Rs.

Based on: V.I. Vasenev, J.J. Stoorvogel, N.D. Ananyeva, K.V. Ivashchenko, M.M. Vizirskaya, R. Valentini 2015 Basal respiration – a proxy to understand spatial variability of soil CO_2 emissions in urban regions. *Submitted*

5.1. Introduction

Soil is the largest pool of actively cycling carbon in terrestrial ecosystems, containing about 1500-2000 Pg (10^{15} g) C in various forms (Swift, 2001; Janzen, 2004). Although soils are major carbon sinks, they also have potential to emit carbon through soil respiration (Rs) (Houghton, 2003; Chapin III et al., 2009). This represent the predominant terrestrial CO_2 fluxes from land to atmosphere (Raich et al., 2002; Schulze, 2006). Rs, including autotrophic respiration of root systems and root-associated organisms, and heterotrophic respiration of free-leaving microorganisms in the soil (Chapin et al., 2006; Gomes-Casanovas et al., 2012) represent a “destructive brunch” of terrestrial carbon cycle (Nilsson et al., 2000; Valentini et al., 2000; Kurganova, 2010). CO_2 emissions due to Rs contribute to depletion of soil carbon stocks and is though important to predict temporal dynamics of soil carbon stocks (Coleman and Jenkinson, 1996; Parton, 2001; Komarov et al., 2003).

Rs varies significantly in space and time. Different Rs is obtained depending on soil types, ecosystem types and biomes, contributing to spatial variability of Rs (Islam and Weil, 2000; Hamilton et al., 2002; Cruvinel et al., 2011; Fromin et al., 2012). Temporal variation is given by short-term (days, months) and long-terms (years, decades) trends. Daily and seasonal variation is mainly influenced by fluctuations in bioclimatic factors, including soil temperature and moisture. Long-term variation in Rs is usually driven by land-use change (Guo and Gifford, 2002; IPCC, 2005, 2013). Substantial increase in Rs is reported after deforestation (Hughes et al., 1999; Thuille et al., 2000), and during the first years after conversion of natural areas into croplands (Ivanov et al., 2004; Galford et al., 2010). Significant changes also occur when abandoned agricultural lands are recolonized by natural vegetation (Kurganova et al., 2007; Vuichard et al., 2008).

In comparison to natural and agricultural areas, much less is known so far about urban soils’ respiration and urbanization effect on Rs. Urban sites are generally assumed to be an assemblage of build-up areas and artificial soils, mostly associated to green zones within towns which cover a small percentage of the overall surface. This standpoint is one of the main reasons why urban areas are often neglected in regional and global carbon assessments. However, this is just a partial view of the overall picture. In fact, a territory of a city district can include green zones, parks, urban forests and even grasslands and croplands (Naizheng et al., 2012; Vasenev et al., 2013b, 2014). Sport and ornamental green lawns can occupy up to 40% of the non-sealed city territory (Milesi et al., 2005). Soils, which occur in urban areas, can have very different origin from being part of what remains of the original natural ecosystems to completely artificial infrastructures.

Urban soils are very heterogeneous and can be exposed to a wide variety of management regimes and disturbances. This provides conditions for significant differences in Rs. Considering discussed temporal dynamics of Rs, this makes analyzing spatial variability of urban soils' respiration very complex. Spatial variability of Rs can be assessed by both direct and indirect methods but the implementation of these research methods differs.

Direct methods, based on repeated *in situ* measurements, are relatively expensive and time and labor intensive. They are therefore only applied on a limited number of plots. To apply this approach for larger regions, the study area is stratified (e.g. based on soil or land-use type) with measurement taken only at a limited number of representative sites (Nilsson et al., 2000; Kurganova, 2010). By relying on these representative sites, the spatial variation within each strata is not considered.

Alternatively, indirect methods estimate Rs as a function of proxy variables, such as reflected radiation for remote sensing approaches (Guo et al., 2011; Huang et al., 2013) or soil microbiological activity parameters measured under standardized conditions, such as basal respiration (BR) (see section 2.2). BR is determined by measuring CO_2 produced by soil microorganisms after pre-incubation under standardized temperature and moisture conditions (Anderson and Domsch, 1988; Creamer et al., 2014). The method allows for the comparison of different samples (e.g. taken at different locations or moments in time) making the long-term monitoring unnecessary. BR is less informative than direct measurements in terms of absolute respiration ratios butdata on its performance and a predictor of RS spatial variability are lacking.

This research assesses the potential of direct and indirect measurements of Rs to understand its spatial heterogeneity in very heterogeneous and different urban ecosystems. The study was implemented for the a area in Moscow city, representing contrast land-use types (urban forest, cropland and lawns) in similar climatic conditions and lithological conditions.

5.2. Material and methods

5.2.1 Test area in the Moscow city

Moscow city is located in the southern mixed forests vegetation subzone of the taiga-forest zone. The experimental area belongs to the most southern part of the Klinsko-Dmitrovskaya chine's slope. Relief is represented mainly by moraine hilly plain and moraine loam is the main parent material. Zonal Eutric Podzoluvisols are the most diffused soil type in the area (FAO, 1988; Shishov and Voitovich, 2002). The climate in Moscow city is humid continental with an average July temperature of 19.1°C and an average January temperature of -14.0°C. In winter, temperatures normally drop to approximately −10.0°C, though warm periods with temperature rising above 0.0°C can occur. The average number of days with temperature below zero varies from 151 to 197. This number clearly decreaes during the last decades. The average annual precipitation is close to 650mm. Summer period lasts from mid-May to the beginning of September, whereas winter - from the beginning of November to the end of March, with snow cover starting around the beginning of November and melting generally at the beginning of April (Naumov et al., 2009).

A $10km^2$ test area, for which both direct and indirect measurement of Rs took place, is located in the North of Moscow city (N55°50'; E37°33'). The area includes three adjacent sites with similar climatic and lithological conditions but with different land-use: forest, cropland and urban. Land use in the area has been stable in the at least last 50 years. The forest site is characterized by typical mixed-forest species such as pine, lime, birch, maple, oak, elm and larch. Sod-podzolic soils (Eutric and Stagnic Podzoluvisols) dominate in the area. Measuring plots were located on a catena including top, slope and bottom positions. Cropland site is characterized by a four-field crop rotation, including winter wheat – potatoes – barley - grassland (vetch-oats mixture). Eutric podzoluvisols dominate at this plot, although here they possess some evidences of agrogenic transformation due to soil tillage (Mazirov & Safonov, 2010). Sampling took place on barley plot under minimal tillage. The urban site includes green lawns under different forms of management: i) managed lawns (irrigation, fertilization, and moving) and abandoned lawns (no care was taken except for non-regular cutting). Abandoned lawns also include two categories contrasting in intensity of anthropogenic pressure: high and low, whereas observed managed lawns were experiencing high anthropogenic pressure only. Low pressure refers to ornamental lawns located at the courts far from highways and main traffic routes. High anthropogenic pressure refers to lawns subject to high recreational load, located close to the major pathways and roads. Different sub-types of Urban Technosols are found in the area: Urbanozems, Replantozems and urban constructed soils (Gerasimova et al., 2003; FAO, 2007; Prokofyeva et al., 2011). Sampling was carried out on the plots, representing different combination of management and anthropogenic intensity factors.

5.2.2 Soil sampling and respiration measurements in the test area

Soil profiles up to 100cm were analyzed for each of the plots to understand differences in soil morphology and distinguish the depth of organic horizon for further sampling. For each profile, a geographical reference was made, the color on the Munsell chart was determined under field conditions, and the soil texture was analyzed by the Zakharov method (Smagin, 2003). Soil profile descriptions were used to classify investigated soils, following Russian and international soil classification (FAO, 1988; Tonkonogov et al., 2004; Rossiter, 2007; Prokofyeva et al, 2011).

The variability of Rs in Moscow probably coincides with the spatial variation in terms of climate, soils, vegetation, and land use, as well as its temporal dynamic due to diurnal and seasonal variability. Sampling design allowed considering both temporal and spatial variability. Temporal variability was assessed through direct Rs measurements. For direct Rs measurements, experimental plots of 25-50m^2 were established in each of the three sites. The number of plots per site varied: one in cropland, four in urban lawns and five in the forest area (Table 5.1, Figure 5.1). In each plot, Rs was measured using the chamber approach with an infrared gas analyzer Li-820 (Li-Cor, USA) (Figure 5.2). Each Rs measurement was followed by measuring of the topsoil (0-10cm) temperature (Checktemp thermometer, Hanna, Germany) and moisture (SM-300 probe, Delta-T, UK). This resulted in a total of 50 measuring points per sampling event. Measurements were taken over the season 2013-2014 with different intervals. At first, a diurnal dynamic was measured at each of the sites to understand Rs daily fluctuations and determine the representative time period for further measurements. Diurnal Rs dynamics was analyzed based on the 24 hours measurements with three hours interval, performed at one representative plot from each site at the third week of July 2013 – the middle of the growing season. Afterwards, measurements were taken every ten days during the growing season in May-September, when the most considerable dynamics was expected, and every 30 days in October-April, when low respiration rates were assumed due to cold climatic conditions (Kurganova et al., 2011). Winter measurements were taken only at the selected plots, because of limited availability of some green lawns and cropland sites under the snow cover. Abandoned urban lawn site was observed only in 2013, whereas measurements at the two other urban lawn sited continued in 2014.

Figure 5.1 Allocation of the experimental sites (1 - urban forest, 2 - green lawns, 3 - cropland areas)

Table 5.1 Experimental design for *in situ* measurements of Rs

Site	Location	Land-cover	Soil type	Plots	# of points for direct measurements	# of points for indirect measurements
Forest	55°49´N/ 37°33´E	Mixed forest	Eutric and Stagnic Podzoluvisols	Top of the hill	5	3
				Slope	10	6
				Bottom of the hill	10	6
Cropland	55°50´N/ 37°34´E	Four-field crop rotation	Agric Eutric Podzoluvisols	Barley under minimal tillage	5	3
Urban	55°50´N/ 37°33´E	Green lawn	Technosols	Managed/ high pressure	5	2
				Abandoned/ high pressure	5	6
				Abandoned / low pressure	10	6

Whereas Rs spatial variability was analyzed only by direct repeated in situ measurements, both direct and indirect approaches were used to assess Rs spatial variability. Spatial variability of in situ Rs was assessed through variance, standard deviation, standard error and coefficient of variance for each site and for the whole test area in each measuring period. Indirectly, spatial variability was assessed based on the BR measurements, taken in standardized conditions.

In order to check the comparability of indirect BR and direct in situ approaches as tools to describe Rs variability we analyzed soil BR at the same sites where in situ Rs was observed, but for a limited number of points (n=32; Table 5.1). Sampling points for BR measurements were located one meter from the collars for in situ Rs measurements (Figure 5.2). This allowed considering similar soil conditions. Soil samples were taken from the upper soil horizons and then mixed to 0-10cm (topsoil) and 10-40cm (subsoil). The choice of the layers was based on the assumption that soil microbiological activity significantly varies with depth. The 0-10cm layer is traditionally analyzed in soil microbiological research (Anderson and Domsch, 1988; Ananyeva et al., 2008; Creamer et al., 2014). Deeper soil layers are rarely studied. We analyzed a composite sample from 10cm to 40cm deep to improve our understanding of subsoil's contribution to microbiological activity including BR. The choice of the 40cm depth as the lower boundary for soil sampling was determined by the previous evidences, showing that 50-70% of soil microbiological activity in Eutric Podzoluvisols and in urban soils in similar climatic conditions is concentrated in top 30-50cm (Lorenz and Kandeler, 2005; Susyan et al., 2006; 2009). We also considered that 40cm was the maximal depth of humus-accumulative horizon in the observed soils. We didn't analyze BR for the subsoil below 40cm at the test area, since we didn't expect considerable microbiological activity there, however this differed our sampling approach from those we implemented at the regional scale.

A B C

Figure 5.2. Measuring soil respiration *in situ* using the chamber approach: A- modified Li-820; B- soil collar; C – measuring chamber.

Prior to the respiration analysis, the soil samples (100-150 g) were moistened up to 50-60% of their water holding capacity and incubated in aerated plastic bags at 22°C for 7 days (Anderson and Domsch, 1977; Ananyeva et al., 2008). The soil was preconditioned for one week at an optimal temperature and moisture before the determination of BR to avoid microbial activation during sample preparation (mixing, sieving, moistening). Subsamples (2 g) for respiration measurements were taken from the pre-incubated soil sample and placed in a vial (15 ml volume) in 4 replicas. The vial was kept tightly closed and the time course was recorded. Soil subsamples were incubated for 24 h at 22°C after which BR was estimated as the CO2 efflux. Headspace gas samples were collected and subsequently the CO2 evolution was quantified using a Chrom-5 model gas chromatograph equipped with a thermal conductivity detector. BR rate was expressed as μg CO2-C g-1 soil h-1 and re-estimated for the mass of dry soil (105°C, 8 hours) (Anderson and Domsch, 1977; Ananyeva et al., 2008). To standardize for air CO2, we collected air samples in 4 replicas inside the room where the vials were sealed, analyzed CO2 concentration in these air samples on gas chromatograph and subtracted the results from ones obtained for soil samples.

We used available data on SOC contents and acidity in 0-10cm and 10-30cm and 30-50cm (mixed samples) collected for the same observation plots at the test area with an independent soil survey (RUSFLUXNET project, Vasenev et al., 2014) for better explanation of the soil features and their possible influence on Rs and BR. The pHKCl (with a soil : KCl ratio of 1 : 2.5) was measured and the SOC content was determined by dichromate oxidation (Vorobyova, 1998).

5.2.3. Data processing and statistical analysis.

The Rs measurement and BR sampling were performed in five to ten spatial replicates per plot depending on the expected heterogeneity. Ten replicates were taken for the most heterogeneous urban soils, whereas five replicas were taken for more homogeneous cropland and forest sites. The different number of sampling points was further considered, when estimating standard errors. In the laboratory BR measurements from each soil sample were performed in four replicates. The results were calculated for dry soil (105°C, 8h) and expressed as the mean ± standard error.

Spatial variability of Rs and BR was characterized by the coefficient of variance (CV) per site and the coherence between the CV’s was explored by Pearson’s correlation coefficient. Normality of the distribution of Rs values was checked by Shapiro-Wilk’s W test and homogeneous of variances was checked by Levene’s test. Factorial analysis of variance

(ANOVA) and Tukey multiple comparison test were implemented at first to test significance of the difference in chemical features, respiration, soil temperature and moisture between observed sites and different time periods (one-way ANOVA) and afterwards to analyze contribution of temporal and spatial components to total Rs variability (two-way ANOVA). To achieve the latter we analyzed CV in all the sites for one similar time point (to understand the spatial variability) and CV for the three representative sites separately (to understand time dynamics). The contribution of each factor was assessed through the explained variance value (ω^2) estimated using the formula:

ω^2=(SS_F-dfMS_{within} / SS_{total}+MS_{within})×100%,

where SS_a, sum of squares for the factor; df, degree of freedom; SS_{total}, total sum of squares; MS_{within}, mean square of inter-group variability (Quinn, Keough, 2002).

At the final stage spatial variation of BR expressed in CV was analyzed for the test area and per site and compared to the results obtained by chamber approach. We implemented linear regression model to estimate the fit of CV values given by direct and indirect measurements. The predictive power of each statistical model was characterized by the coefficients of determination R^2 and R^2_{adj}. Statistical analysis was performed in STATISTICA 6.0 (Borovikov, 2003).

5.3. Results

5.3.1 Soil features

The close proximity of the analyzed sites assured to have comparable climatic conditions and the similar lithological origin for all the investigated soils. Differences in soil morphological features were mainly determined by anthropogenic disturbance, which gets evident when comparing soil profiles at the forest and urban lawns sites. Eutric Podzoluvisols in the forest site possessed all the typical morphological features of illuvial-eluvial type of soil formation: light sandy-loamy E horizon and darker loamy B horizon with manganese-iron inclusion. Topsoil organic horizon was 10cm to 15cm deep with the maximal depth at the bottom positions of the catena. Litter horizon was partly destroyed and partly mixed with A horizon due to anthropogenic disturbance and we considered mixed A+O topsoil organic horizon. Soils observed at the bottom position also possessed evidences of gleization process. Illuvial - eluvial features were described for the soil profile at the cropland site as well but substantial agrogenic transformations were found. For example, topsoil Ap horizon was mixed to the depth of 0-25cm and eluvial horizon was not evident. This probably is a consequence of previous tillage. Soils at the urban lawns were exposed to the highest anthropogenic disturbances which resulted in evident features of urban pedogenesis: transformed residuals of construction material (bricks, lime, asphalt etc.), introduced horizon (sandy TCH layer) and buried 'natural' horizons at the bottom part of the soil profile (Table 5.2). These features of anthropogenictransformations were more evident for the managed urban lawn site with high anthropogenic pressure, whereas soil profile at the abandoned lawn exposed to low anthropogenic pressure lacked these features. The depth of the topsoil organic horizons varied from 10-15cm in the forest to 26-40cm at the urban sites and we selected the 0-10cm and 10-40cm layers for analyzing basal respiration.

Table 5.2 Descriptions of the soil profiles at the research plots

horizon	depth	color	texture	horizon	depth	color	texture	horizon	depth	color	texture
Forest site											
Top position				Slope position				Bottom position			
(O)+ A	0- 10	10YR3/3	SL	(O)+ A	0-11	10YR3/3	SL	(O)+ A	0-15	10YR3/3	SL
AE	11-16	10YR5/3	SL	AE	12-22	10YR5/3	SL	AE	16-20	10YR5/3	SL
E	17-42	7.5YR4/6	LS	E	23-30	7.5YR4/2	LS	E	21-25	7.5YR4/2	LS
EB	43-64	7.5YR4/2	SL	EB	31-65	7.5Y5/6	SL	Ebg	26-55	5Y5/2	SL
Bt	65-80	7.5YR4/3	L	Bt	66-80	10YR4/4	L	Btg	56-80	7.5Y5/6	L
BC	81-100	5YR4/6	L	BC	81-100	10YR6/5	L	BCg	81-100	G15/5GY	L
Urban sites											
Managed				Abandoned (high pressure)				Abandoned (low pressure)			
AY	0-38	10YR4/3	SL	AY	0-40	10YR3/1	SL	AY	0-26	10YR2/2	L
U1	39-56	10YR5/4	L	TCH	41-51	7.5YR4/6	S	EB	27-55	7.5YR4/6	SL
U2	67-75	7.5YR4/6	L	U	52-76	10YR4/4	L	B1	56-77	10YR4/4	LS
[EB]	76-100	7.5YR4/2	L	[Bt]	77-100	7.5YR4/3	L	B2t	77-100	10YR5/4	LS
Cropland site											
				AY	0-26	10YR2/2	L				
				EB	27-55	7.5YR4/6	SL				
				B1	56-77	10YR4/4	LS				
				B2t	77-100	10YR5/4	LS				

Data on soil chemical features, analyzed for the research sites via an independent soil survey RUSFLUXNET project; Vasenev et al., 2014) and aggregated for the layers 0-10cm, 10-30cm and 30-50cm confirmed our assumption of anthropogenic disturbance as the main factor influencing soil features at the test area. Urban forest soils, which were less exposed to anthropogenicinfluence and disturbance, showed the lowest pH and the highest average SOC concentration. Cropland soils contained significantly less SOC than all the others and pH values were significantly higher than in the forest, but lower than in urban lawns. Urban soil's pH was close to neutral. This is likely explained by random presence of concrete particles and other materials used in building construction which can raise pH in these acidic soils (Gerasimova et al., 2003). Spatial variability in SOC concentrations in urban lawns was substantially higher that at the other sites, with coefficient of variance achieving 40% at some points. SOC decrease over profile was more abrupt comparing to rather smooth changes in forest soils (Table 5.3).

Table 5.3 Soil chemical features at the test area

layer	pH_{KCl}	SOC(%)	layer	pH_{KCl}	SOC(%)	layer	pH_{KCl}	SOC(%)
Forest site								
Top position			Slope position			Bottom position		
0-10	3.91±0.16	3.1±0.77	0-10	3.96±0.24	2.22±0.36	0-10	3.76±0.14	3.34±0.54
10-30	3.58±0.14	1.6±0.21	10-30	4.01±0.13	1.76±0.09	10-30	3.83±0.11	1.8±0.32
30-50	3.68±0.12	0.9±0.29	30-50	3.81±0.15	1.38±0.15	30-50	3.89±015	1.43±0.15
Urban sites								
Managed			Abandoned (high pressure)			Abandoned (low pressure)		
0-10	6.7±0.05	2.4±0.09	0-10	6.1±0.15	2.35±0.34	0-10	6.25±0.10	1.22±0.15
10-30	6.3±0.11	1.0±0.13	10-30	5.78±0.10	1.13±0.15	10-30	6.13±0.09	0.7±0.22
30-50	5.4±0.11	0.4±0.15	30-50	5.5±0.11	0.7±0.21	30-50	5.54±0.08	0.6±0.15
Cropland site								
			0-10	5.16±0.13	1.04±0.13			
			10-30	4.26±0.11	0.67±0.08			
			30-50	4.14±0.08	0.42±0.08			

5.3.2. Rs temporal dynamics at the test area in Moscow city

Temporal trends of Rs variability at the test areas included both diurnal fluctuations and dynamic within the season. Average daily Rs from the urban lawns was 60% higher than at the forest sites and almost five times higher than at the cropland. However, monitoring results highlighted similar diurnal trend for all three sites: maximal Rs was obtained for the period between 7AM and 13-16PM with further decrease at night time. Average Rs measured for these time periods was comparable (90-130%) to the average daily respiration. Positive correlation was found between Rs and soil and air temperature dynamic during the day (r varied from 0.41 in the forest to 0.61 at the cropland site). Positive correlation between Rs and soil moisture was also found for the cropland site, which can present moisture as a limiting factor for Rs at this time of the season, when soil water is scarce. Although the difference between average Rs values per observed time intervals were not always statistically significant, the diurnal trends were clear and similar for all the sites, which allowed considering the time period between 7AM and 13PM relevant for measuring Rs seasonal dynamics (Figure 5.3).

Seasonal dynamics confirmed our assumption of the highest Rs from urban lawns comparing to all the other sites. This trend was observed all over the year, getting more evident during the growing season, when the highest Rs values at all the sites were obtained. Significant decrease in Rs was shown during the winter season for all the sites, when average Rs got below 10 $gCO_2\ m^{-2}day^{-1}$. In spring when air and soil temperatures at the day time overpassed

10ºC threshold a rapid increase in Rs was observed at all the sites with the maximal average values for the urban lawns (Figure 5.4).

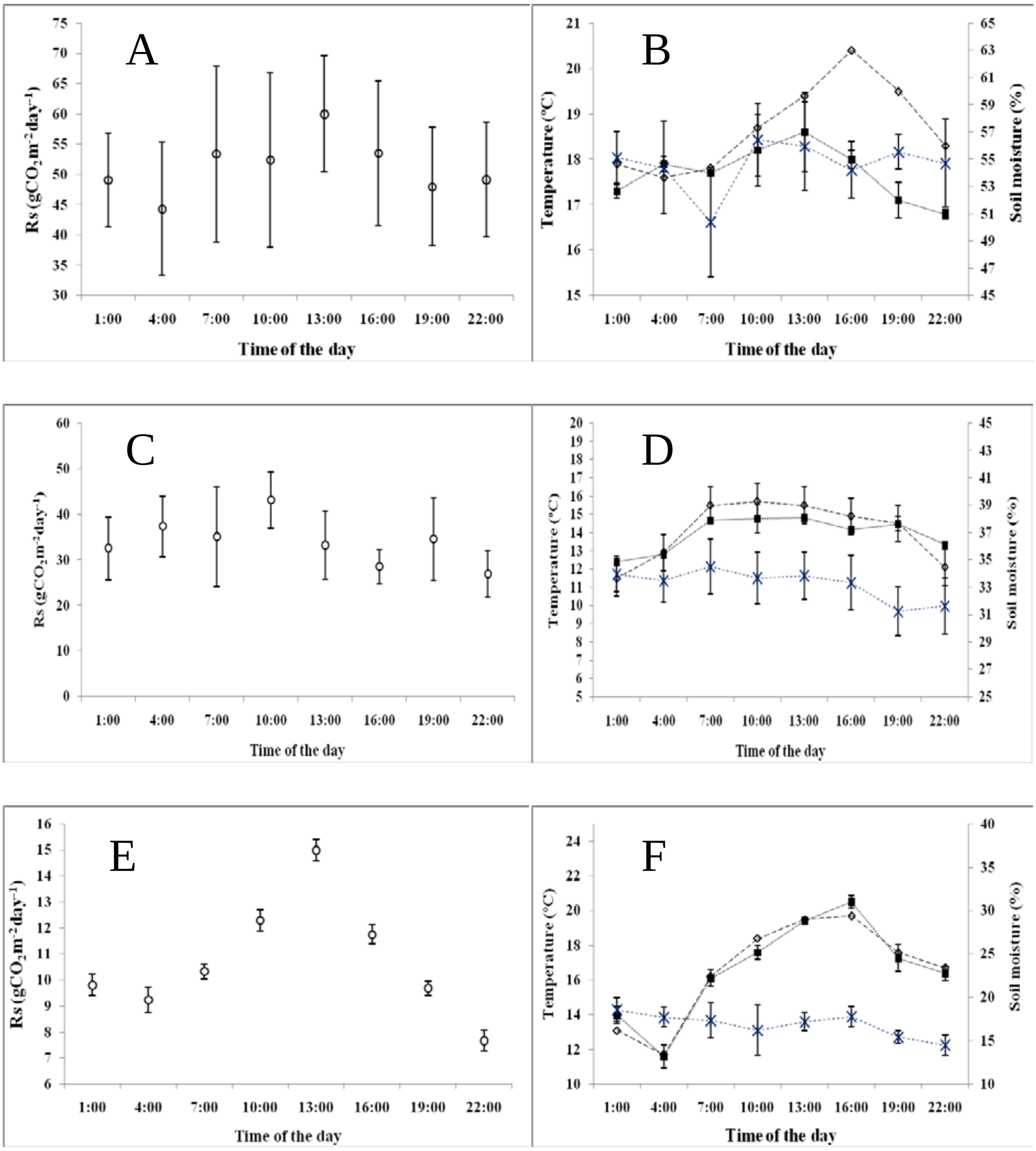


Figure 5.3 Diurnal dynamics of Rs, air temperature, soil temperature and soil moisture at the urban lawns (A and B), forest (C and D) and cropland E and F sites)

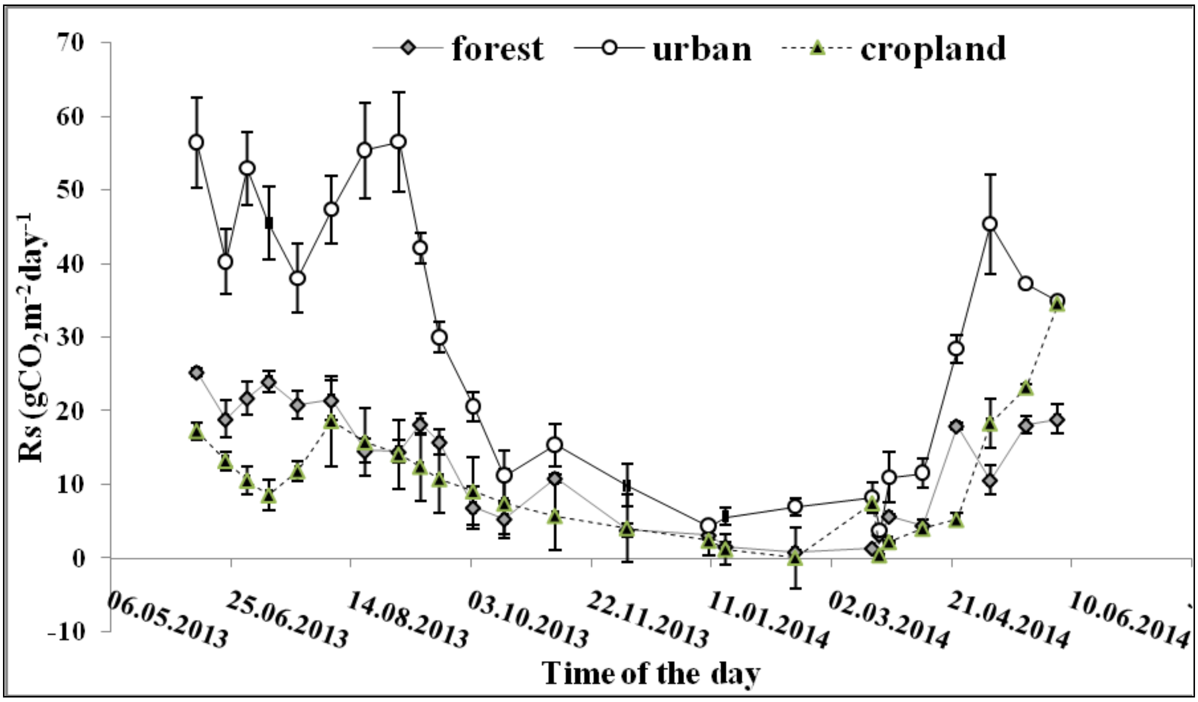
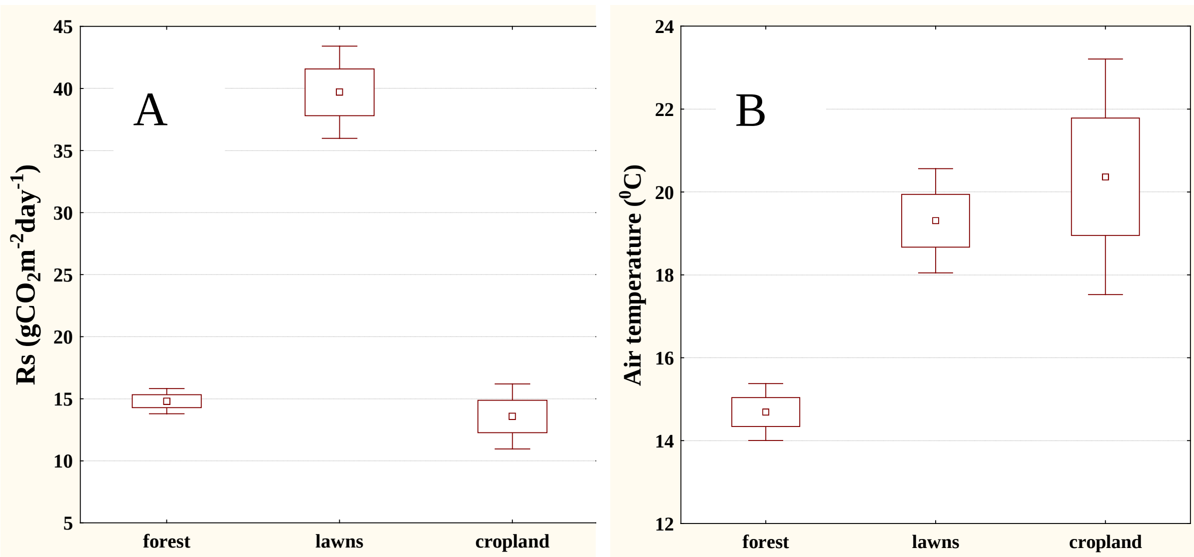


Figure 5.4 Seasonal dynamics of Rs at the urban lawns, forest and cropland sites at the test area in Moscow city

When averaged for the year, Rs from urban lawns was twice as high as in the forest and three times higher, than in croplands. Average air and soil temperature and moisture also differed between the sites significantly: the driest and warmest conditions were found for the cropland, whereas soil and air temperature in the forest was the lowest and moisture – the highest in comparison to other sites (Figure 5.5). Seasonal dynamic in Rs at the test area was significantly influenced by changes in soil temperature ($p<0.001$), whereas the effect of soil moisture was not significant ($p=0.224$). However, both factors explained only 25% of the total variance in Rs (R^2_{adj} = 0.25), which was likely resulted from high spatial variability between and within the sites (Table 5.4).



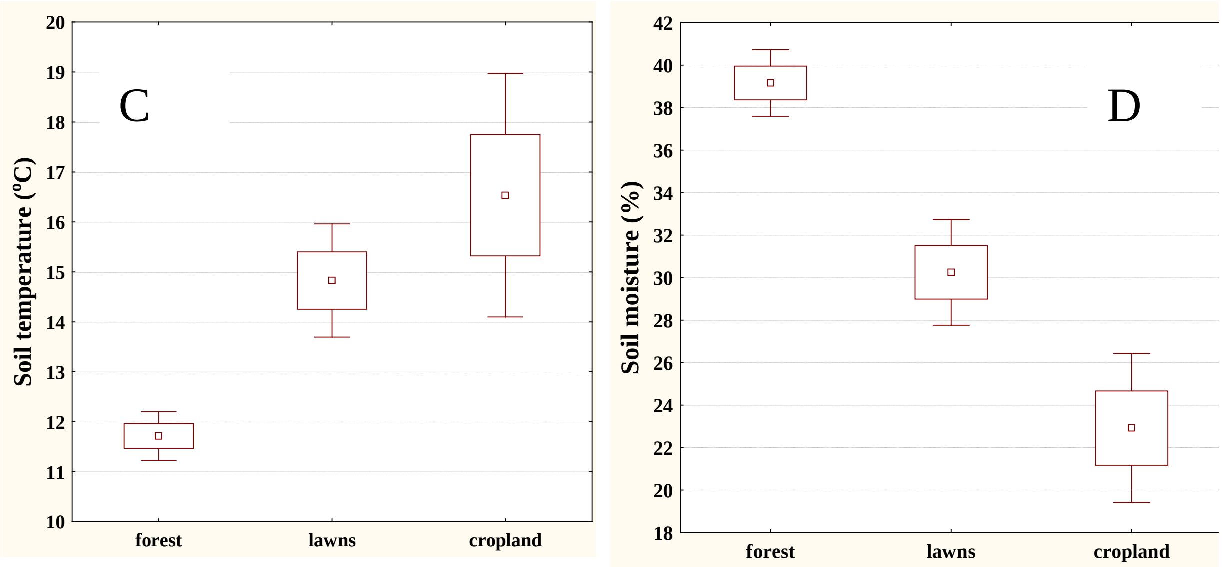


Figure 5.5 Average seasonal Rs, air temperature, soil temperature and moisture at the urban lawns, forest and cropland sites at the test area in Moscow city

When different sites were analyzed separately the significance of influencing factors and explained variance differed. Soil temperature was a predominant factor at the forest site and urban lawns ($p<0.001$), whereas moisture effect at these sites was insignificant ($p>0.100$). The opposite was shown for the cropland, where moisture effect ($p<0.05$) and soil temperature was not significant. This outcome corresponds to one described for the diurnal dynamics at the cropland site and likely results from the limiting effect water scarcity has on Rs in summer period. This is confirmed by the lowest average soil moisture obtained for the cropland (Figure 5.5.).

Table 5.4 Results of limear regression models, relating seasonal Rs to soil moisture and temperature, aggregated for the test area and for the research sites

Parameter	β	SE of β	B	Se of B	t	p-level
Rs at the test area related to soil temperature (st) and soil moisture (sm) (R^2= 0.25; R^2_{adj} = 0.25)						
Intercept			2.745	2.771	0.991	0.322
st	0.495	0.039	1.491	0.118	12.656	0.000
sm	-0.013	0.039	-0.015	0.045	-0.326	0.745
Rs at the forest site related to soil temperature (st) and soil moisture (sm) (R^2= 0.29; R^2_{adj} = 0.29)						
Intercept			3.897	2.236	1.743	0.082
st	0.506	0.050	1.061	0.104	10.215	0.000
sm	-0.060	0.050	-0.039	0.032	-1.218	0.224
Rs at the cropland site related to soil temperature (st) and soil moisture (sm) (R^2= 0.17; R^2_{adj} = 0.14)						
Intercept			20.100	6.424	3.129	0.003
st	0.017	0.194	0.018	0.208	0.086	0.932
sm	-0.399	0.194	-0.298	0.145	-2.060	0.045
Rs at the urban lawn site related to soil temperature (st) and soil moisture (sm) (R^2= 0.32; R^2_{adj} = 0.31)						
Intercept			8.384	5.052	1.660	0.099
st	0.578	0.064	1.894	0.211	8.989	0.000
sm	0.071	0.064	0.105	0.096	1.098	0.274

Explained variance varied from the lowest 17% for the cropland to 29% for the forest and 31% for the urban lawns, which confirms our assumption on high spatial variability within the research sites (Table 5.4).

5.3.3. Rs spatial variability at the test area in Moscow city

Rs was highly variable at the test area - the mean and standard deviation (SD) of 16.4. and 8.19 g CO_2 $m^{-2}day^{-1}$ resulted in a CV of 49%. Average assessment given for the sites was confirmed when analyzing average Rs for observation plots. Rs was in good coherence with the level of disturbance with the maximal efflux given by managed green lawns experiencing high anthropogenic pressure. This trend is indirectly confirmed by positive significant correlation between Rs and pH_{KCl} in the observed layers (r = 0.84; 0.88 and 0.89 for 0-10, 10-30 and 30-50 layers respectively, $p< 0.05$ for all the layers), which is a widely used indicator of urban soil disturbance in boreal climate since urban soils effected by sedimentation of cement dust from building construction likely possesses alkaline pH_{KCl} compared to the acid pH of the natural zonal soils (Gerasimova et al., 2003) (Figure 5.6). Further segregation of the dataset and analysis of CV for individual plots gave range from 50 to 88%, which included both spatial and temporal components of Rs variability.

In order to assess spatial variability apart from temporal dynamics we compared CV of Rs for individual plots measured at the same date. The first measuring date of each month was taken for comparison. We focused on the period June to October 2013, when the highest Rs was observed at all the sites and also when data from all the observation plots was available. The CV values estimated for the analyzed period ranged from 5-10 to more than 50% for the majority of the pots. No clear temporal trend in CV was found for all the plots except to cropland where variance was continuously increasing over the season. In average CV in green lawns was comparable or slightly higher than in the forest and cropland although the difference was not statistically significant (Table 5.5).

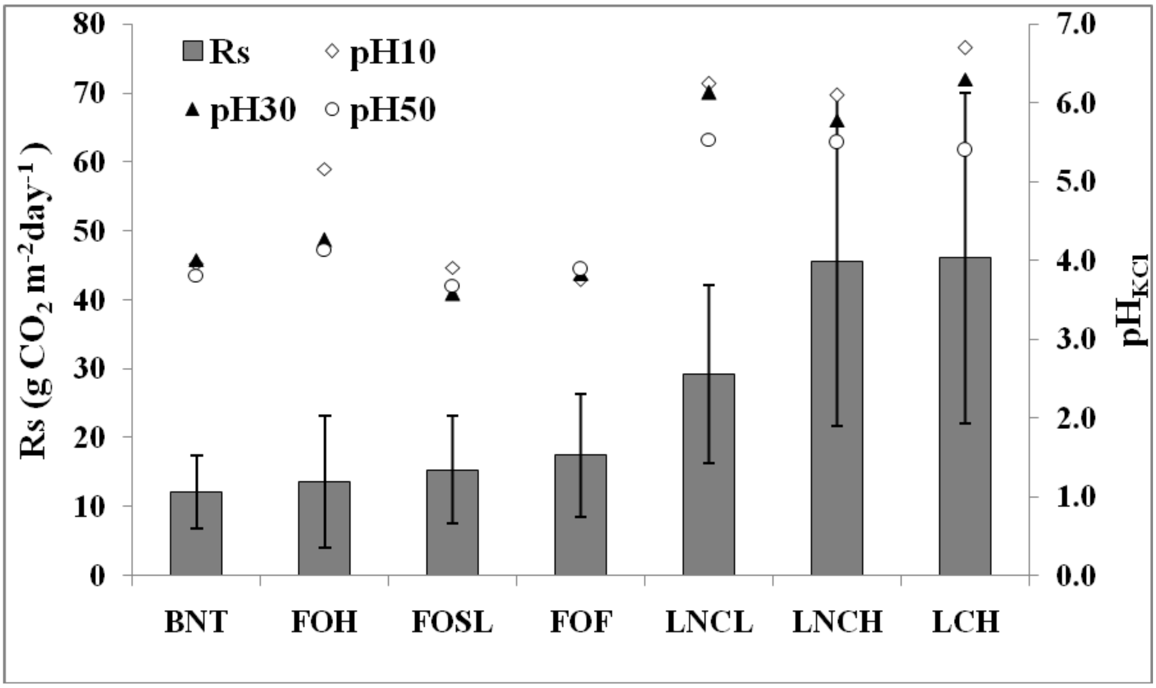


Figure 5.6 Average Rs and pH for the layer 0-10 (pH10), 10-30 (pH30) and 30-50(pH50) at the monitoring plots at the test area. (BNT – barley under minimal tillage; FOH – forest, top of the hill; FOSL – forest, slope; FOF – forest, foot of the hill; LNCL – abandoned urban lawn, exposed to low anthropogenic pressure; LNCH – abandoned urban lawn, exposed to high anthropogenic pressure; LCH – managed urban lawn high

Table 5.5 Coefficient of variance (CV%) of in situ Rs for the main test area in Moscow city

Land-use	Sites	June	July	August	September	October	Average for growing season
Forest	Top of the hill	39	8	24	51	40	58
	Slope	44	30	30	44	34	39
	Bottom of the hill	27	35	26	29	14	42
Cropland	Barley under minimal tillage	15	39	38	65	70	45
Urban	Managed	26	18	41	11	41	38
	Abandoned/ high pressure	40	5	22	36	4	53
	Abandoned/ low pressure	27	32	24	18	34	40

We analyzed the contribution of space and time factors into the total variance of Rs during the growing season by performing a two-way factorial ANOVA. The 'time' factor was presented by measuring decades, coded from 1 (the first decade of June) to 10 (the first decade of October). The 'space' factor was given by seven observed monitoring plots. Factorial ANOVA results confirmed significant effect of 'time' and 'space' factors and teheir combination on Rs, air and soil temperature and soil moisture ($p<0.001$) (Table 5.6).

Table 5.6 Factorial ANOVA results

General effects	df	SS	MS	F	p
Soil respiration (R^2=0.77)					
Time	7	20227.7	2889.66	29.4023	0.000
Space	9	102898.3	11433.15	116.3323	0.000
Time × Space	79	21428.4	271.25	2.7599	0.000
Error	562	55233.4	98.28		
Total	659	237109.3			
Air temperature (R^2=0.97)					
Time	7	10833.99	1547.712	1096.487	0.000
Space	9	3444.04	382.671	271.106	0.000
Time × Space	79	2178.87	27.581	19.540	0.000
Error	562	793.27	1.412		
Total	659	22999.42			
Soil temperature (R^2=0.91)					
Time	7	7032.70	1004.671	386.2007	0.000
Space	9	2061.29	229.033	88.0413	0.000
Time × Space	79	1896.03	24.000	9.2259	0.000
Error	562	1462.00	2.601		
Total	659	15609.87			
Soil moisture (R^2=0.73)					
Time	7	24447.3	3492.476	61.63204	0.000
Space	9	18551.0	2061.219	36.37452	0.000
Time × Space	79	14863.5	188.145	3.32022	0.000
Error	562	31846.6	56.667		
Total	659	118558.8			

Statistical model explained a large part of parameter’s variation: R^2_{adj}= 0.96, 0.89, 0.73 and 0.76 for air temperature, soil temperature, soil moisure and soil respiration respectively. The contribution of the observed factors to the Rs total variance differed. Spatial factor explained 44% of total variance, whereas spatial factor and the combination of space and time factors contribute to only 9% each. The opposite trend was found for the other parameters. Temporal factor dominated for air and soil temperature, expalining 47% and 45% of total variance, whereas spatial factor contributed only to 15% and 13% correspondingly. All the factors ‘space’, ‘time’ and ‘space’ × ‘time’ showed similar contribution to the total variance of soil moisture, expaining 20%, 16% and 13% respectively. Outcomce form ANOVA analysis presents spatial component as the major one in Rs varibility at the test area, whereas abiotic soil conditions (temperature and mositure) were more influenced by the temporal dynamics.

5.3.4. Variability of BR in comparison to in situ Rs measurements

BR was measured in the test area at 32 points located close by the Rs measuring collars during a single sampling campaign. As a result, it only describes the spatial variability. The highest topsoil BR was obtained for the forest sites whereas the lowest was found in the cropland. Managed urban lawns showed less BR than abandoned lawns. Higher BR in natural sites, compared to disturbed sites is a very likely trend widely described in literature (Ananyeva et al., 2008; Gavrilenko et al., 2011). We also found positive correlation between BR and SOC contents: r = 0.82 ($p < 0.05$) for the topsoil, and r = 0.75 ($p < 0.05$) and r = 0.51 ($p > 0.05$) for subsoil BR and SOC content in 10-30cm and 20-50cm layers respectively. This finding confirms BR as an indicator strongly related to soil chemical features and carbon stocks above of all (Creamer et al., 2014; Figure 5.7).

Although topsoil BR traditionally surpasses subsoil BR, average BR values for both layer were strongly positively correlated (r = 0.80, $p < 0.05$) and the CV of the BR measurements only showed a small difference between the layers. Total variability was estimated at 52% and 48% for topsoil and subsoil respectively. This was about 10% less than one reported based on the *in situ* measurements on average for the growing season (Table 5.7)

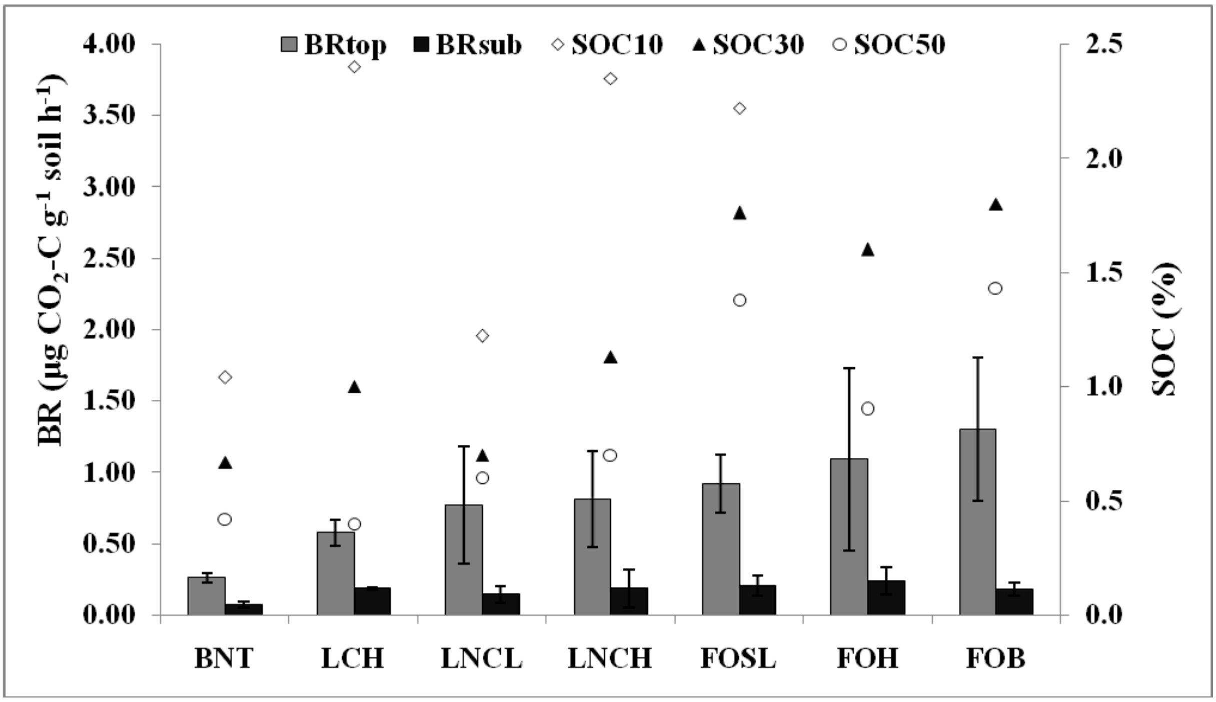


Figure 5.7 Average topsoil and subsoil BR and SOC contnetns for the layer 0-10 (SOC10), 10-30 (SOC30) and 30-50(SOC50) at the monitoring plots at the test area (see Figure 5.6 for abbreviations)

Table 5.7 Coefficient of variance (in %) estimated for BR and *in situ* Rs averaged for the 2013 season on the test area in Moscow city (n: number of observations; CV_{top}: CV in topsoil BR; CV_{sub}: CV in subsoil BR)

Land-use	Sites	Rs		BR		
		n	CV	n	CV_{top}	CV_{sub}
Forest	Top of the hill	32	58	3	59	41
	Slope	80	39	6	22	36
	Bottom of the hill	78	42	6	39	26
Cropland	Barley under minimal tillage	72	26	3	17	41
Urban	Managed	42	38	2	16	4
	Abandoned/ high pressure	38	45	6	42	73
	Abandoned/ low pressure	91	40	6	54	40

Averaged Rs and BR values at the key plot didn't show significant correlation, however, comparison between CV results estimated based on BR and CV values of *in situ* Rs averaged for the growing season showed strong coherence for all the plots, excluding for abandoned lawns under low pressure (r = 0.53 for all the sites and r = 0.83 when abandoned lawns under low pressure are excluded) (Figure 5.8).

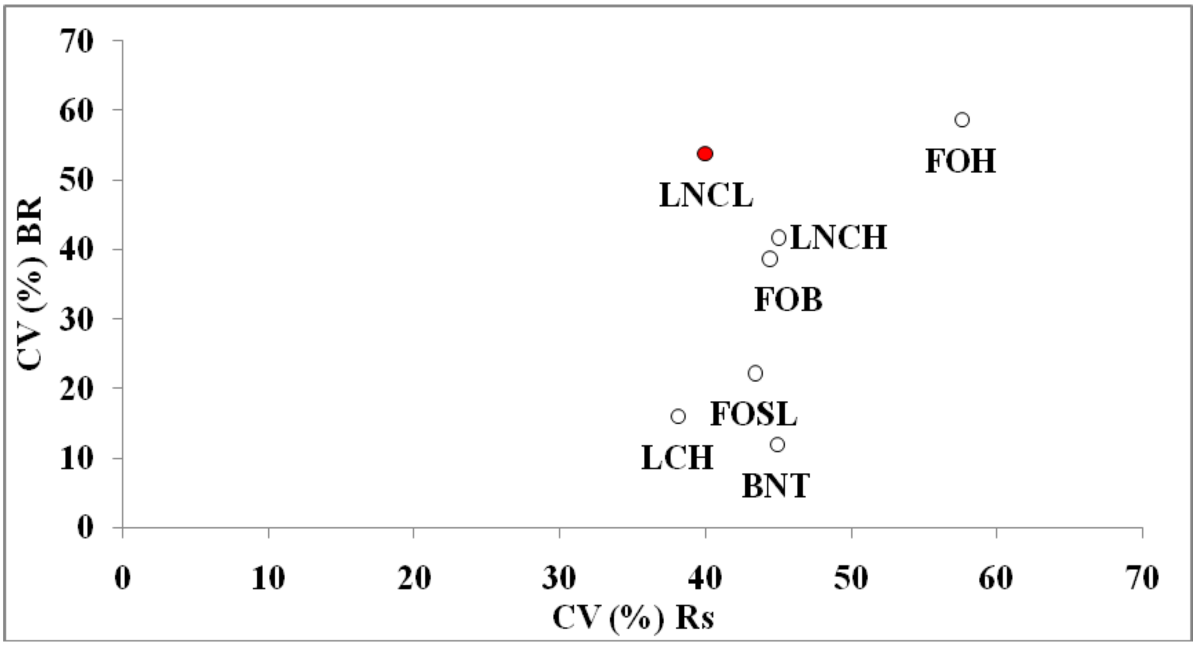


Figure 5.8 Comparison between CV predicted based on topsoil and subsoil basal respiration and estimated from in situ Rs measurements for the test area in Moscow region.

The reason for the fall-out of this plot was an unexpectedly high value of 1.54 µg CO_2-C g^{-1} soil h^{-1}, obtained for one of the sampling points. The value was 50% higher than average of the other 5 points from the plot and higher than at any other observation point at the urban lawn site. Since we also observed the highest SOC value for the point, high BR was likely caused by some urban soil artifact, rich in carbon (like coal or turf peace). We decided not to exclude this point since the total number of BR observation was already limited and this resulted in high BR CV for the site, which was larger than Rs CV, contrasting to majority of observation plots. The positive significant correlation between CV, obtained by direct and indirect approaches, confirms the assumption that BR is a relevant proxy to capture spatial variability in Rs.

5.4. Discussion

5.4.1 Soil respiration in urban, forest and cropland sites of the test area

Observations of Rs under adjacent land-use types presented high spatial variability with the highest Rs obtained for green lawns. Chemical properties and management of the urban soil are the most likely factors, influencing Rs. Higher Rs in urban areas compared to non-urban is often explained by topsoil SOC exceeding one in natural and agricultural areas (Qian & Follet, 2002; Zircle et al., 2011; Vasenev et al., 2013a). Urban topsoil regularly contains turf particles, organic wastes and substrates (Lorenz & Lal, 2009; Picket et al., 2011), thus its chemical quality and stability is low (Beyer et al., 2001; Lorenz et al., 2006) and mineralization rates are rather high, resulting in high respiration rate (Garcia et al., 2012). We didn't observe significant differences in SOC between urban and non-disturbed sites at the test area, whereas difference in Rs was significant. Apparently, lawn management (irrigation, fertilization, cutting) and physical disturbance increased Rs through influencing soil temperature and water regimes as well as having an effect on soil microbial community (Cheng et al., 2008). The disturbance effect on Rs was also confirmed by the highest absolute values obtained for the managed lawns and under high anthropogenic pressure in comparison to abandoned ones.

A different relationship was obtained for BR with the highest values in natural areas, which surpassed ones in disturbed urban and cropland sites from 20% to almost three times. This outcome is in good coherence with many studies reporting lower rates of soil microbiological activity, including BR, in managed and anthropogenic disturbed areas with more stressful conditions for microorganisms (Nortcliff, 2002; Ritz et al., 2009).Different response of Rs and BR to disturbance illustrates mechanisms underlying both indicators. Rs is sensitive to instantaneous effect of anthropogenic pressure, dynamic of soil temperature and moisture (Ana Rey et al., 2002; Kurganova, 2010). BR is likely the function of more stable soil chemical features and prolonged anthropogenic influence (Ananyeva, 2003; Vasenev et al., 2012).

5.4.2 Temporal-spatial variability of soil respiration at the test area

Both temporal and spatial variability of Rs at the research sites was analyzed. Spatial variability was addressed through at first diurnal and then seasonal dynamics, resulting in the trends often described for Rs temporal dynamics. Positive correlation between soil temperature and Rs obtained both within the day and during the season for all the sites highlights soil temperature as the major driving factor for Rs, which is usually reported for the temperate climate, where heat becomes a limiting environmental factor (Kudeyarov et al., 2007; Kurganova, 2010). Soil moisture was important mainly during the summer season and mainly for the cropland, exposed to the direct sun light, comparing to more shady forest and urban lawns site. Although Rs's temporal dynamics was influenced by temperature and partly moisture, significant difference in Rs between the sites remained all over the daytime and season. This highlights spatial variability as a major component of total Rs variance, which was tested during the vegetation season.

The experimental scheme with contrasting plots within land-use and continuous measurements during the vegetation season captured Rs variability at the test area ($R^2 = 0.77$; $p < 0.05$ for the Factorial ANOVA with "space", "time" and "space" × "time" as factors). Temporal variability in Rs obtained for the test site mainly referred to the seasonal changes in the air and soil temperature This relationship is very typical for Rs (Ana Rey et al., 2002; Frank et al., 2006; Kurganova et al., 2011). Influence of soil moisture was more evident during the dry season from July to September, whereas in the cold period the influence of the factor was insignificant. BR didn't allow to capture temporal variability in Rs although it was very variable in space, strongly dependent on land-use. High spatial variability at the test area was also reported for Rs. Urban sites contributed considerably to the spatial variability of Rs and BR. For both indicators CV values in major part of the urban plots were higher than ones for forest and croplands. This well corresponds with the studies comparing Rs in urban and non-urban areas (Kaye et al., 2005; Zhang el al., 2010) and doubts some regional and global assessments where urban Rs is neglected (Baron et al., 1997; Running et al., 2000; Nilsson et al., 2000). In general, spatial heterogeneity contributed to total variability in Rs almost two times more than temporal dynamics. This was confirmed by higher CV values and ANOVA results and witnesses on the considerable role of land-use and land cover in Rs's variability, especially in the very heterogeneous urbanized areas.

5.4.3 Comparison of BR and in situ chamber approaches for the analysis of Rs variability

Analysis of the Rs at the test area showed that: i) spatial heterogeneity was the main source of Rs variance and ii) even with high density of observations in space and time (in average 5 points/km^2, 9 repetitions each), less than 60% of the total variability was captured. Expansion of direct Rs measurements for the scale of Moscow region considering its size, heterogeneity and necessity for repeated measurements would have been impossible. The alternative approach to measure BR at the regional level and compare it with direct measurements within a small test area seems to be a very attractive alternative.

Spatial patterns in Rs measured by direct and indirect approached were not similar. For instance, the in situ chamber measurements showed the highest averaged Rs in urban areas, whereas BR in urban soils were lower than in forests and meadows. The reason is that BR is strongly linked to chemical soil conditions, influencing the soil microbial community (C and N content, pH, contamination etc.) and thus characterizes the potential CO2 emission. In contrast, in situ Rs measurements are very sensitive to soil temperature and water regimes and especially to physical disturbing which is a very common condition in urban areas.

Although the absolute values of BR and Rs at the test area were not correlated, spatial variability, representing the major source of total Rs variance of over the season, was similarly captured by both indicators. Positive correlations between CV of BR and Rs obtained for the test area proved relevance of BR as Rs proxy. CV values obtained for the observation sites, 10% lower, than once from chamber approach, seem logical, since BR captured only spatial variability whereas Rs also represented the temporal trends. However, with a limited number of observations (in average 3 points km-2 without repetitions in time) BR approach performed almost with the same quality as the in situ chamber method. The chamber approach can be preferred at the local scale, since it not only explains total variability but also enables understanding of the spatial and temporal components. In addition, its results can directly be linked to actual soil CO2 efflux. However, for the regional analysis BR was proven as a relevant alternative.

5.5. Conclusion

Rs is a principal carbon efflux. Empirical data on Rs is considerably biased to natural and agricultural systems compared to urban areas. Rs is highly variable in space and very dynamic. This spatial-temporal variability is further complicated by high short-distance heterogeneity of urban soils. Lack of methodology to capture this variability constrains our understanding of urban Rs, which remains very uncertain so far. In our research we analyzed temporal dynamic and spatial variability of Rs in contrast land-use types: urban lawns, forest and croplands, located within a 10km^2 test area in Moscow city.

Although spatial and temporal variability at all observed location was high, average Rs at the urban lawns was significantly higher than at the non-urban sites. This finding presents urban soils as important sources of CO_2 emissions and highlights their role in carbon cycle.

We implemented direct (Rs) and indirect (BR) approaches to compare Rs and its spatial variability in urban and adjacent non-urban sites. Two alternative approaches yielded two different trends. In situ Rs of urban soil was significantly higher than in adjacent cropland (managed) and forest (natural) soils and was the most variable one. In contrast, the highest BR was obtained for forest sites and was negatively affected by anthropogenic disturbance. Different trends reported refer to different drivers behind two processes. Rs is more affected by instantaneous factors, like temperature, moisture and physical disturbance, whereas BR likely illustrates soil conditions for potential CO_2 efflux. Although absolute values, obtained for BR and Rs were different, patterns in spatial variation were very similar. Both approaches confirmed that the extremely variable urban environment leads to very high spatial heterogeneity of Rs, with coefficients of variance higher than 60% and 2-3 times higher than reported in forest and cropland sites, highlighting the difficulty of characterizing this CO_2 source. Rs measurements can not be substituted by BR in terms of absolute flux values or temporal (daily, seasonal) monitoring, however BR was proven to be a robust proxy to capture the spatial variability of Rs, that is especially essential when shifting from the local to the regional scale of analysis.

Acknowledgements

The project was partly supported by Governmental Grant # 11.G34.31.0079, RF President project № MK.3962.2014.4 and RFBR project №14-04-31901. The authors thank Pavel Lakeev, Irma Elvira Ade and Dmitry Gusev for assistance with the field measurement and Dr. Julia Kurbatova for valuable suggestions and useful comments.

6 BASAL RESPIRATION AS A PROXY TO UNDERSTAND SPATIAL TRENDS IN CO_2 EMISSIONS IN THE MOSCOW REGION

ABSTRACT

Soil respiration (Rs) is an important terrestrial CO_2 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.

Based on: V.I. Vasenev, J.J. Stoorvogel, N.D. Ananyeva, K.V. Ivashchenko, M.M. Vizirskaya, R. Valentini 2015 Basal respiration – a proxy to understand spatial variability of soil CO_2 emissions in urban regions. *Submitted.*

6.1. Introduction

Soil respiration (Rs) causes an annual efflux of 80 Pg carbon to the atmosphere and is the largest carbon efflux of terrestrial ecosystems (Schulze, 2006; Bond-Lamberty and Thomson, 2010a). This efflux is almost ten times that released by fossil-fuel emissions (Raich and Tufekcioglu, 2000). The CO_2 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 (Bond-Lamberty and Thomson, 2010b; Creamer et al., 2014).

Rs depends largely on a range of soil abiotic and biotic parameters (Carlyle and Than, 1988; Gomes-Casanovas et al., 2012). 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 (Yuste et al., 2007; Kuzyakov and Gavrichkova, 2010). Regional and global Rs variability is typically represented by average Rs rates for different land-uses and soil types (Raich and Tufekcioglu, 2000; Hamilton et al., 2002; Houghton, 2003a; Ananyeva et al., 2008). So far, the spatial heterogeneity of Rs remains inadequately understood (Trumbore, 2006; Kudeyarov et al., 2007). 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. Islam and Weil, 2000; Hamilton et al., 2002; Larionova et al., 2010; Kurganova et al., 2011). Urban areas received very limited attention. Due to a number of specific factors and conditions, like soil sealing and zoning (Scalenghe and Marsan, 2009; Pickett et al., 2011), 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 (Vasenev et al., 2013a). 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 CO_2 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 (Buyanovsky et al., 1986) and a variety of chamber approaches (open-path, closed-path, and dynamic close chambers) (Nakadai et al., 1993; Bekku et al., 1997; Savage and Davidson, 2002). 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 (Nilsson et al., 2000; Kurganova, 2010). 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 (Pell et al., 2006). 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 (Winding et al., 2005; Bispo et al., 2009). BR is determined by measuring CO_2 produced by soil microorganisms after pre-incubation under standardized temperature and moisture conditions (Anderson and Domsch, 1988; Creamer et al., 2014). BR thus characterizes the potential soil CO_2 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 (Bloem et al., 2006). 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 (Wilson & Baldocchi, 2000; Baldocchi et al, 2001).

6.2. Materials and methods

6.2.1 Moscow Region

Moscow Region extents over 46,700 km^2. 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 temperatures range between 3.5°C to 5.8°C. Average annual rainfall varies from 780mm in the north to 520mm 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 (Shishov and Voitovich, 2002; Naumov et al., 2009). Parent material includes moraine loam and clay in the north and center, fluvioglacial 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) (Shishov and Voitovich, 2002). 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 (Egorov et al., 1977; FAO, 1988; Shishov et al., 2004). 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.

6.2.2 Analyzing regional Basal Respiration's spatial variability

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 (Figure 6.1).

Inside each stratum, sampling plots were selected randomly. For each plot, 5 topsoil (0-10cm) samples were taken from a 2 m^2 square plot (corners and center) and pooled into a single composite sample. A single sample was taken from the subsoil (10-150cm) 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 10-150cm. 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 150cm 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.

Samples were sieved (2mm) 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 150cm depths at some points. To consider this we implemented correction coefficient on cut-off profiles when estimating BR in urban subsoil. More details on the sampling design were described in Vasenev et al, 2013c; 2014b.

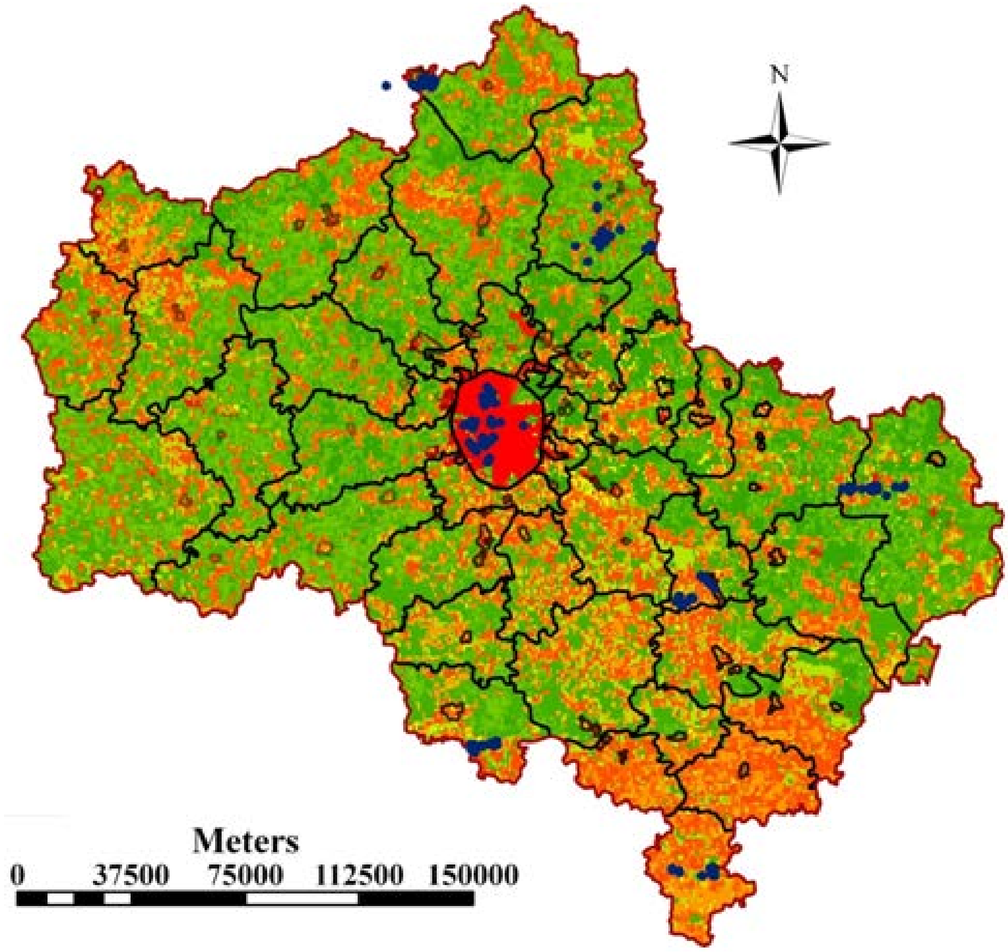


Figure 6.1 The level of urbanization in Moscow region ranging from natural (green) to urban (red) with the location of the observation points

<u>Mapping BR and analysis of variability</u>

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 (Anderson and Domsch, 1986; Wardle, 1992; Ananyeva et al., 2008), the SOC content was also added as an explanatory variable, based on the 771m resolution map of carbon contents and stocks derived for the region (Vasenev et al., 2014b).

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 (derived from RFSSS, 2012). 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 (Vasenev et al., 2013c).

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^2adj 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 771m 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 (Borovikov, 2003). Visualization and GIS analysis was carried out in ArcGIS (Harder et al., 2011).

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.

6.3. Results

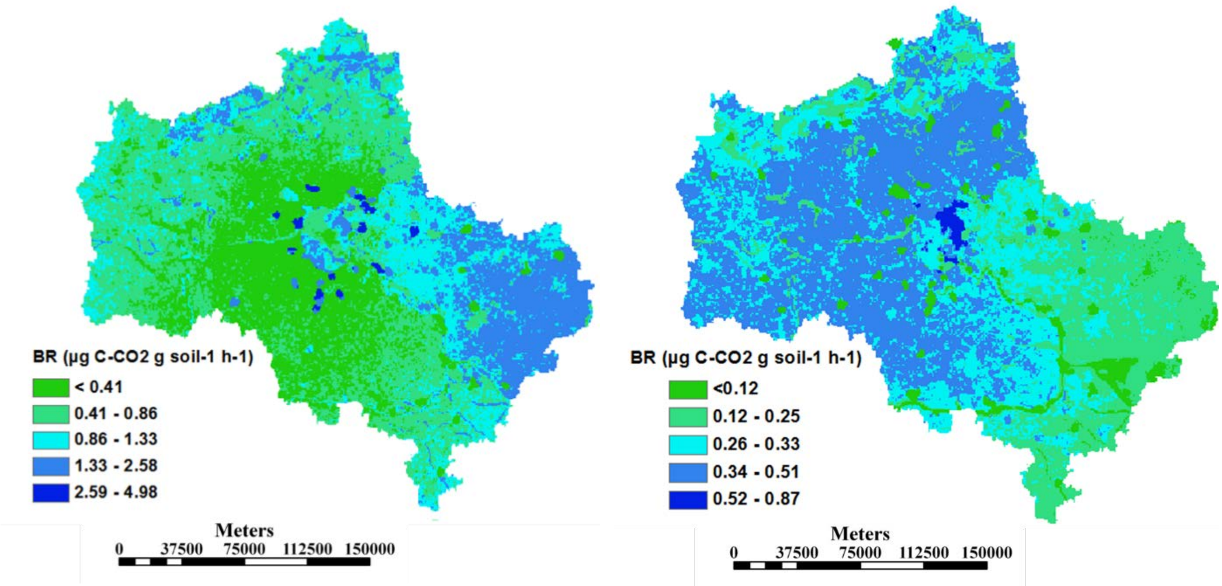
6.3.1 BR in the Moscow Region

Modelled BR values for the entire Moscow Region showed a high spatial variability with averages of 0.75±0.57 µg CO_2-C g^{-1} soil h^{-1} for the topsoil and 0.25±0.17 µg CO_2-C g^{-1} 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 6.1).

Table 6.1 Basal respiration in Moscow region averaged over land-uses and soil types.

Factor	N	Topsoil BR (µg CO_2-C g^{-1} soil h^{-1})			Subsoil BR (µg CO_2-C g^{-1} soil h^{-1})		
		mean	SD	CV (%)	mean	SD	CV (%)
Land-use							
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
Soil type							
eutric Podzoluvisols &	108	0.76	0.50	66	0.28	0.20	70
dystric Histosols 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.6.2 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 (Figure 6.2 B).



A B

Figure 6.2 Basal respiration (µg CO_2-C g^{-1} soil h^{-1}) of topsoil (A) and subsoil (B) in the Moscow Region

6.3.2 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 (Figure 6.3).

6.4. Discussion

6.4.1 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 771m 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 (Baldocchi et al, 2001; Bond-Lamberty and Thomson, 2010a), thus the opportunity to evaluate our results based on ones from literature was very limited. Analysis, available at the country scale (Nilsson et al., 2002; Kurganova, 2010) 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 (Fridland, 1988), thus uncertainty is very likely.

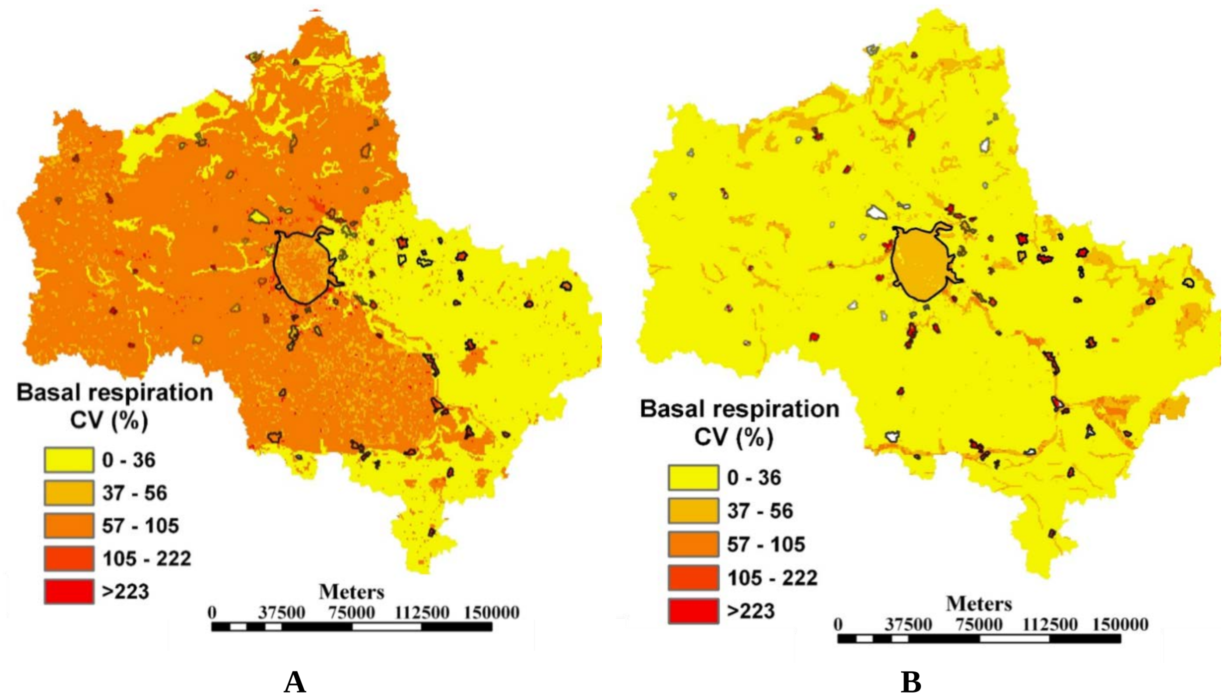


Figure 6.3 Coefficient of variance (CV%) of topsoil (A) and subsoil (B) basal respiration in Moscow region

Patterns of BR between and within different soils types and land-uses were analyzed and showed a good correspondence with literature. For example, our lowest mean for the urban areas in comparison to forest, meadow and agricultural ones corresponds with Beyer et al. (1995), Ananyeva et al. (2008) and Gavrilenko et al. (2011). 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 (Shishov and Voitovich, 2002; Vasenev et al., 2014b) confirming the concept of BR as an indicator for respiration of soil organic matter - based microbes (Creamer et al., 2014). This outcome also corresponds well with the relationship between BR and SOC obtained for the test area in Chapter 5.

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 (Kaye et al., 2005; Vasenev et al., 2013a) and the outcomes obtained at the test area (see Chapter 5). 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 (Jo and McPherson, 1995; Pouyat et al., 2006; Lorenz and Lal, 2009) 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 (Blume et al., 2002; Susyan et al., 2006). 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" (Alexandrovskaya and Alexandrovskiy, 2000; Lorenz and Kandeler, 2005; Vasenev et al., 2013c). 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.

6.4.2 Uncertainties in BR maps of Moscow Region

Predictive power of the GLMs implemented for BR mapping estimated by R^2_{adj} = 0.51 and 0.38 for topsoil and subsoil correspondingly indicates that 50 to 60% of total variability remained unexplained ant 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 (see Vasenev et al., 2014b) 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 (Gavrilenko et al., 2011; Vasenev et al., 2012). We also introduced reduction coefficient to consider impervious soils, however there are evidences in literature that soil sealing results not only in decrease of Rs at the sealed areas, but also in increase of CO_2 emissions from adjacent open territories (Smagin, 2005; Scalendhe and Marsan, 2009). Comparison between topsoil and subsoil BR also was not straightforward since differences in sampling approaches and aggregating 10-150cm 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.

6.4.3 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 Rs and BR. Total Rs includes autotrophic respiration of root systems and root-associated organisms and heterotrophic respiration of free-leaving microorganisms in the soil (Chapin et al., 2006; Gomes-Casanovas et al., 2012), whereas BR refers only for the heterotrophic component. Moreover, disturbing and pre-incubation procedures influence the CO_2 production by microorganisms (Creamer et al., 2014) and makes comparison between absolute values of BR and *in situ* Rs rather challenging.

So, BR is rather questionable as a tool to measure actual Rs, 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 Rs'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 Rs mainly based on the vegetation indexes (Huang et al., 2013) 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 (Minasny et al., 2013) and slightly lower than the statistical model based on *in situ* Rs for the test site, described in Chapter 5.

6.5 Conclusion

Soil respiration (Rs) is an important terrestrial CO_2 efflux. Although the most comprehensive global Rs database (Bond-Lamberty and Thomson, 2010a) 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 constrains 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 CO_2 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 (Grimmond et al., 2002; Pataki et al., 2006) 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 Governmental Grant # 11.G34.31.0079, RF President project № MK.3962.2014.4, RFBR project №14-04-31901 and the Wageningen University Sandwich Fellowship Program. The authors thank Ilya Mazirov, Anna Epikhina 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.

7 NET EFFECT OF URBANIZATION ON CARBON STOCKS: THE CASE OF MOSCOW REGION

ABSTRACT

Urbanization is responsible for large environmental changes worldwide. Urbanization was traditionally related to negative environmental impacts, but recent research highlights the potential to increase soil carbon (C) stocks in urban areas. The net effect of urbanization on soil C is, however, poorly understood. Negative influences of infrastructure construction and soil sealing can be compensated by establishing of green areas. We explored the possible future net effects of urbanization on soil C-stocks in the Moscow Region. Urbanization was modelled as a function of environmental, socio-economic and neighbourhood factors. This yielded three alternative scenarios: i) including neighbourhood factors; ii) excluding neighbourhood factors and focusing on environmental drivers; and iii) considering the New Moscow Project, establishing 1500km^2 of new urbanized area following governmental regulation. All three scenarios showed substantial urbanization on 500 to 2000km^2 former forests and arable lands. Our analysis shows a positive net effect on SOC stocks of 5 to 11 TgC. The highest increase occurred in the less fertile Orthic Podzols and Eutric Podzoluvisols, whereas C-storage in Orthic Luvisols, Luvic Chernozems, Dystric Histosols and Eutric Luvisols increased less. Subsoil C-stocks were much more affected with an extra 4 to 10 TgC than those in the topsoils. The highest increase of both topsoil and subsoil C stocks occurred in the New Moscow scenario with the highest urbanization. Even when the relatively high uncertainties of the absolute C-values are considered, a clear positive net effect of urbanization on C-stocks is apparent. This highlights the potential of cities to enhance C-storage. This will progressively become more important in the future following the increasing world-wide urbanization.

Based on: Vasenev V.I., Stoorvogel J.J., Leemans R.., Valentini R. 2015. Net effect of urbanization on carbon stocks: the case of Moscow Region. Submitted.

7.1. Introduction

Urbanization is increasingly important when studying land-use change. The global extent of urban areas quadrupled between 1970 and 2000 (Seto, 2011) and in the beginning of the 21st century urban populations overtook rural populations. Two-thirds of the world's population is projected to live in cities by 2050 (UN, 2008; FAO, 2013). This urbanization coincides with a substantial alteration of soils and vegetation when new urban ecosystems are formed (Pickett et al., 2011). Historically, urbanization was related to negative environmental impacts, such as soil, water and atmospheric pollution (Stroganova et al., 1997; Walsh et al., 2007), forest degradation (Miller, 2012) and biodiversity loss (Lysak et al., 2000; McKinney, 2006). However, recent studies highlight the potential of urban areas to provide and support important services, such as decreasing and treating storm water runoff (Xiao and McPherson, 2002; Pataki et al., 2011), mitigating air pollution (Nowak et al., 2006; Dadvand et al., 2015) and enhancing carbon (C) and nitrogen storage (Lorenz and Lal, 2009; Raciti et al., 2008; Morel et al., 2014). C-sequestration is a key soil function, supporting soil fertility maintenance and climate mitigation (Lal, 2004; Blum, 2005). Studies, however, disagree on the capacity of urban soils to enhance C-storage. The available soil organic carbon (SOC) stocks in urban areas vary from negligible (Craul, 1999; Schaldach and Alcamo, 2007; Schulp and Verburg, 2009) to comparable with natural soils or even surpassing natural soils (Pouyat et al, 2006; Raciti et al., 2011; Vasenev et al., 2013c).

Urbanization results in complex processes that have versatile effects on SOC stocks. Building infrastructure (houses, roads, industries etc.) has a direct anthropogenic influence on soils and can result in considerable SOC losses through excavation of the fertile topsoil and replacing natural and agricultural landscapes by impervious areas (Elvidge et al., 2004; Kaye et al., 2005; Raciti et al., 2012). However, establishing urban green infrastructure (parks, lawns etc.) likely increases soil C-storage (Svirejeva-Hopkins et al., 2004; Zircle et al., 2011). For example, the high SOC stocks in urban lawns is caused by adding artificial substrates, such as turf, peat and organic compost (Lorenz and Lal, 2009; Vasenev et al., 2014a), and by stimulating extra belowground biomass through management practices (e.g. cutting, irrigation, fertilization; Qian et al., 2002; Bandaranayke et al., 2003). Both positive and negative effect of indirect changes in soil-forming factors on SOC in urban soils is possible (Gerasimova et al., 2003). Such factors include urban climate (Voogt and Oke, 2003; Vasenev et al., 2014b), pre-urban land-use (Pouyat et al., 2003; Pickett et al., 2008), mixed and translocated parent materials (e.g. cultural layers and buried horizons; Pouyat et al., 2009; Vasenev et al., 2013a), introduced plant species (Cadenasso et al., 2007) and actual management type and zoning (i.e. industrial, residential or recreational; Raciti et al., 2012; Vasenev et al., 2013a). The effects of urbanization on SOC stocks is thus complex but not yet fully understood, and assessing the changes in SOC stocks is difficult. Considering the high heterogeneity and temporal dynamics of urban soils and addressing the actual allocation of newly-urbanized areas are critical to model net urbanizations' effect on SOC stocks.

In this study, we modelled the effect of urbanization on SOC stocks in the Moscow Region, which is Russian's most urbanized region with Moscow City as the capital. Regional urban areas continued to expand since the 1990s (Garankin et al, 2011). Recently the New Moscow Project was announced by the Russian government (www.mos.ru/en/about/borders) to address urbanization and environmental problems by moving from a metropolitan city to a mega-region (Bashkatova, 2011; Vishnevsky, 2011; Argenbright, 2013). This ambitious project expands the legal borders of Moscow City to more than 2.4 times (up to 2500 km^2) and attracts investments to develop urban infrastructure on this territory (Kvasha and Petrova, 2011). The current governmental policy prioritizes decentralization within the Moscow Region. Rapid urbanization is thus expected within the New Moscow Project in the coming decades and the possible consequences for SOC stocks are not yet estimated. Moscow's Regional Government increased its interest on these consequences. In our study we analysed different plausible urbanization scenarios for Moscow Region, estimated the possible net effect on SOC stocks and highlighted the main hot-spots of C dynamics in the region.

7.2. Study area, data and methods

7.2.1 Study area

The Moscow Region extents over 46,700 km^2 and its territory has a plain relief ranging from 100 meters above sea level in the east to 300 meters in the north and west. The region has a temperate continental climate with mean annual temperatures between 3.5°C to 5.8°C. Average annual rainfall varies from 780mm in the north to 520mm in the south. Parent material includes moraine loam and clay in the north and centre, fluvioglacial sands in the east and west, and cover loam in the south. 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 (Egorov et al., 1977; FAO, 1988; Shishov et al., 2004). Vegetation, which varies with climate, includes three main bioclimatic zones: south-taiga, deciduous forests and steppe-forest (Shishov and Voitovich, 2002).

Anthropogenic landscapes (e.g. agricultural, fallow and urban lands) occupy almost two-thirds of Moscow Region's territory. The urban area is rapidly increasing and currently occupies more than a tenth of the territory and includes 68 cities and towns with 18.8 million inhabitants. Russia's census revealed a 28% increase of Moscow's city population in last two decades (Rosstat, 2012). With a population of over 11.5 million people Moscow City is larger than the next six largest cities in Russia combined, and thus considered as a principal city. Moscow's dominating national role dates back to the 1920s when relocating the capital from Saint Petersburg stimulated its economic development and expansion (Colton, 1995). Moscow grew and became the economic and cultural centre during the Soviet era (Argenbright, 2011). Since the economic and political reforms in the 1990s, the city has utilized new opportunities as an important global financial, political, labour, service, education and tourist centre (Kolosov et al., 2002; 2004; Gritsay, 2004). Its centralized governing structure, rapid population increase and fast development of infrastructure and buildings resulted in intense traffic congestion and environmental pollution (Argenbright, 2008; 2013). In 2006, Moscow City and the broader Moscow Region accounted for more than a quart of the Russian national GDP (Russian Analytical Digest, 2009).

7.2.2 Urbanization: definition and modelling approaches

Many ambiguous definitions of urban areas exist. Raciti et al. (2012), for example, showed for the Boston Metropolitan that inconsistent definitions can result in large differences in predicted SOC-stocks. Conventional definitions use population density (e.g. USCB, 2010; Rosstat, 2010) or economic activity (e.g. Berry, 2008). Such conventional definitions ignore settlements with populations below a certain threshold value. These values, however, can differ between countries. Newly settled build-up areas and cottage villages are frequently excluded and this underestimates urbanization trends. Revising official borders in the databases often also lags with the speed of urban sprawl.

More recent definitions use remote sensing data and estimate urban areas using indicators like the percentage of impervious surface areas (Raciti et al., 2012), the normalized difference vegetation index (Lu and Weng, 2004), the vegetation index built-up index (Stathakis et al., 2012) or the Earth's city lights data (Pandey et al., 2013; Zhou et al., 2014). All these indicators have their own specific limitations. Distinguishing urban areas based on satellite data is accurate, but its classification is constrained by separating, for example, urban green zones (parks, court yards, lawns), non-urban forests and meadows. Many studies define urban areas solely as the built-up areas (e.g. Bhatta et al., 2010; Müller et al., 2010). However, the extent of green zones within urban areas is large and their potential to enhance C-storage is remarkable (c.f. Svirejeva-Hopkins et al., 2004; Milesi and Running., 2005). SOC stocks in urban and non-urban green spaces are different (Zircle et al., 2011; Vasenev et al., 2013a) and should be examined separately

In our study, we considered multiple functional zones (i.e. recreational, residential and industrial), including both impervious (built-up zones, roads, commercial land) and open areas (green zones, parks, lawns) located within the legal urban settlement boundaries, as part of the urban areas. To distinguish between urban and non-urban green zones, we mapped urbanization using historical topographic maps for 1980 (1: 200,000), census data (Rosstat, 2012) and open source web-resources, such as the Open Street Map Project (www.openstreetmap.org). Satellite images helped to validate the resulting boundaries. This combination of imaginary and statistical data showed to be an appropriate technique to start projecting urbanization patterns.

Many approaches have been developed and implemented to model urbanization and its environmental consequences. The most widely used approach is logistic regression (Reilly et al., 2009; Dubovyk et al., 2011) followed by multiple linear regression (Dewan and Yamaguchi, 2009; Seto el al., 2011), bivariate regression (Wu and Zhang, 2012), suitability models (i.e. CLUE-S; Batisani and Yarnal, 2009) and cellular-automata-based models (Sun et al., 2012). Logistic regression is especially suited when data is only available for a limited period (Li et al., 2013). In this study, we used logistic regression to model urbanization's consequences on SOC stocks in the Moscow Region. When implementing this approach, local urbanization probabilities (i.e. per grid cell) are determined as a function of environmental (Reilly et al, 2009; Ye et al., 2011), socio-economic (Wu and Zhang, 2012; Li et al, 2013) and neighbourhood (Müller el al., 2010; Dubovyk et al., 2011) factors.

7.2.3 Analysing urbanization in the Moscow Region in 1980-2014

Urbanization trends for the Moscow Region between 1980 and 2014 were analysed. This period displayed the most rapid urbanization. To avoid spatial misalignments, we implemented a 'backcasting' method (Feranec et al., 2007) in which the maps for earlier periods are generated from the most recent 2014 map. The used open street map described 11,552 urban polygons. However, most polygons were too small to denote a true urban area.

Polygons larger than 2km^2 were further analysed and this yielded 168 settlements. The 2km^2 threshold not only corresponded to the distinct village township limit (Denisov et al., 2008) but also to the accuracy of the 1980 maps. All the selected settlements were validated based on Google Earth images and, if actual boundaries did not match these images, manually edited using ArcGIS 9.3 software. We assumed that, even if a settled zone that fringed an urban area, was not within the area's legal boundaries, this zone was still strongly related to that urban area, had a similar environment and provided a very likely direction for further urbanization.

The final validated urban map of 2014 was used to 'backcast' the 1980-2014 urbanization map. This was done in three steps: i) the 2014 urban map and 1980 topographic map were superimposed; ii) the changes in the legal urban boundaries were detected through visual interpretation; and iii) polygons that showed differences, were adapted. The resulting urbanization map with binary classes (urban and non-urban) was converted to a raster file with a 30m resolution (Figure 7.1).

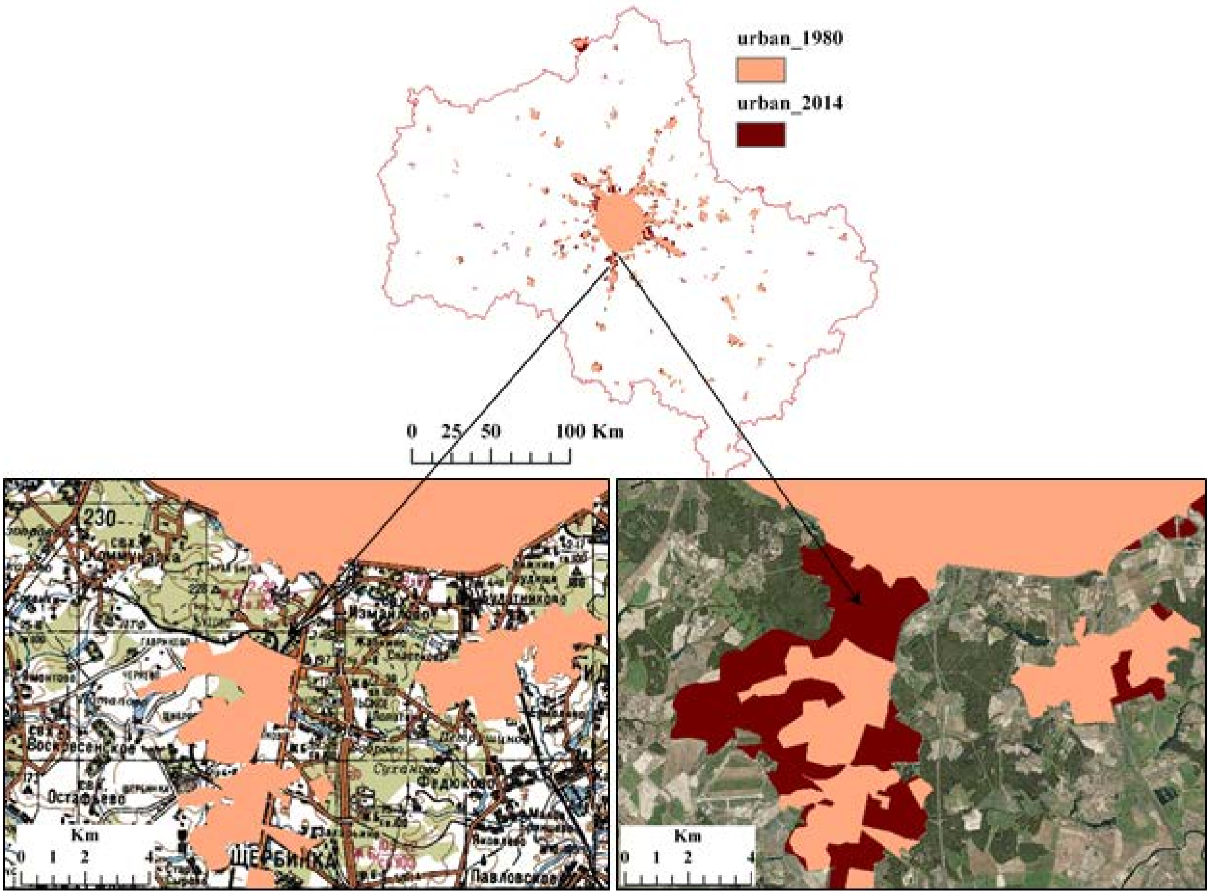


Figure 7.1 Urbanization in 1980-2014 in the Moscow Region

7.2.4 Driving factors behind urbanization

Urbanization was related to several environmental, socio-economic and neighbourhood driving factors (Aspinall, 2004; Batisani and Yarnal, 2009; Li et al., 2013).

Environmental factors indicate a territory's suitability for urbanization and include climatic, ecological and topographic factors (Table 7.1). These factors are critical when analysing urbanization effect on SOC stocks (McBratney et al., 2003; Dobrovolsky and Urussevskaya, 2004; Lal, 2004). We included climate, relief, vegetation and soil type in our analysis. The needed information was derived from available global and regional datasets. Climate conditions were described by the 30 arc-second WorldClim mean annual temperature and total annual precipitation (Hijmans et al., 2005). Slope and elevation were derived from the 90m resolution digital elevation model by Jarvis et al. (2008). Standardized Leaf Area Index (LAI) indicating vegetation differences, was derived from Landsat images for 1981 and 2012. To determine the local seasonal LAI amplitude, we analysed images for both mid-July and mid-October. The exploratory soil map for the Moscow Region (Shishov and Voitovich, 2002) was used to delineate soil patterns. Soils were aggregated into five major groups: Orthic Podzols; Eutric Podzoluvisols; Orthic Luvisols; Luvic Chernozems; and combined Dystric Histosols and Eutric Luvisols (Egorov et al., 1977; FAO, 1988; Shishov et al., 2004).

Socio-economic factors are important to model urbanization (Seto et al., 2011; Wu and Zhang, 2012). Since primary census-based socio-economic variables (e.g. population and GDP) were only available for coarse administrative units and not at the required spatial resolution, we focused on several proximate variables, such as the distance to socio-economic centres, roads and water bodies (Cheng and Masser, 2003; He et al., 2006; Batisani and Yarnal, 2009). Considering the highly centralized structure of the Moscow Region and Moscow City as its main migration attractor (Argenbright, 2013), distances to the Moscow City centre and the main highways were determined. The distances to rivers and lakes were also considered as a possible urbanization predictor. These water bodies provide multiple benefits (e.g. transport and navigation, water supply, recreation, nature conservation and landscape aesthetics). However, neighbourhoods close to water bodies can also experience increased flood risks and impaired drainage. This negatively affects urbanization into these areas (Poelmans and van Rompaey, 2009). All these proximate distances were calculated as the Euclidian nearest distance using the Spatial Analyst routine in ArcGIS 9.3 and based on the available open street maps and additional data from the Environmental Systems Research Institute (Table 7.1).

The neighbourhood is traditionally defined as the proportion of different land-use types in surrounding areas (Stoorvogel and Fresco, 1996; Verburg et al., 2002). Various studies demonstrate that the likelihood of urbanization is much higher at locations surrounded by urban areas (Müller et al., 2010; Li et al., 2013). This is plausible, considering that infrastructural, economic and social conditions usually favour expansion of existing settlements than establishing new ones (Pickett et al., 2011). The proportion of neighbouring urban land is the most frequently used variables in urbanization models (Fang et al., 2005;). We, however, used the percent of urban areas within a 100m and a 1000m radius, since these distances are often used to indicate internal (i.e. influence of urban areas) and external (i.e. influence of non-urban areas) neighbourhood effects. Our neighbourhood factor was calculated applying the focal statistics routine in ArcGIS 9.3 to the 1980 and 2014 maps (Table 7.1). Raster files were compiled with a 771m spatial resolution for the environmental factors and 30m for all socio-economic and neighbourhood factors. The course resolution for the environmental factors was determined by the coarser resolution of their data sources and their assumed lesser short-distance variability

Table 7.1 Factors driving urbanization in the Moscow region

Variable	Description	Source
Environemntal factors		
MAT	Mean annual temperature (°C)	www.worldclim.org
AP	Total annual precipitation (mm)	(Hijmans et al., 2005)
Elevation	Elevation above sea level (m)	srtm.csi.cgiar.org/index.asp
Slope	Slope steepness (°)°	(Jarvis et al., 2008)
LAI_{j81}/ LAI_{j14}	Leaf Area Index (July 12-19th) for 1980 and 2014	http://glcf.umd.edu/data/lai/ (Liang and Xiao, 2012)
LAI_{o81}/ LAI_{o14}	Leaf Area Index (October 16-23th) for 1980 and 2014	
Soil	Aggregated soil types (Soil 1 = podzols; Soil 2 = podzoluvisols; Soil 3 = luvisols; Soil 4 = chernozems; Soil 5 = alluvial and peat	Derived from Shishov and Voinovich, 2002
Socioeconomic factors		
Moscow_d	Euclidian distance to the Moscow city polygon	Derived from the settlement layer www.openstreetmap.org
Highway_d	Euclidian distance to the federal roads	
Water_d	Euclidian distance to the major rivers, lakes and water basins	Derived from the hydrology layer www.openstreetmap.org
Neighborhood factors		
Neighb_100m	Proportion of urban areas within 100m window	Derived from urban map 1980 and 2014
Neighb_1km	Proportion of urban areas within 1000m window	Derived from urban map 1980 and 2014

7.2.5 Statistical analysis

The probability of urbanization for the period 1980-2014 in the Moscow Region was explained as a function of the driving factors using a logistic regression, which relates a binary variable to continuous and categorical predictors (Kleinbaum and Klein, 2010). The first step of our regression analysis included a random sample of 10,000 locations throughout the whole region (including three groups of areas: i) urbanized before 1980; ii) urbanized between 1980 and 2014 and iii) non-urban in 2014.). Only 1% of the sampled locations referred to the second group, therefore an additional random sample of 5000 locations was taken specifically in urban areas. The two datasets were combined and overlaid with all possible explanatory factors. After removing all locations that cannot be urbanized (e.g. located in water bodies) or that have missing values, a dataset with 13,685 locations was created to be used in the regression analysis. A forward stepwise regression approach (based on Wald statistics, which is a testto estimate the prediction's maximal likelihood from binomial data; Borovikov, 2003) was implemented. This approach yielded a model with a binary urbanization dependent variable and a limited number of explanatory variables. The percentage correct predictions was calculated to evaluate the model's performance and R^2 was used to evaluate the model's fit (Nagelkerke, 1991).

7.2.6 Modelling urbanization in 2014-2048 in the Moscow Region

The logistic regression model explained urbanization patterns in the Moscow Region between 1980 and 2014. Two alternative models of urbanization probability were identified. The first model included the environmental, socio-economic and neighbourhood factors that were selected in the statistical analysis. This model is referred as the 'Full Urbanization Model' (FUM). The 'backcasting' method (see Section 7.2.3) should give a dominant effect of and bias toward the neighbourhood factors compared to the socio-economic and environmental factors. To test the role of the neighbourhood factors, we also developed an alternative model that excluded these factors. This model is referred as the 'Environmental Urbanization Model' (EUM). Logistic regression models created the urbanization-probability grid maps. We used these maps to assign urban areas to grids with a pre-defined probability threshold. This threshold was fitted so that the modelled urbanization extent was maximal agreement with the observed extent. Using the minimum resolution of explanatory variables, the 771m urbanization grid maps for 2014 were developed.

Urbanization patterns obtained for the period between 1980 and 2014 (i.e. a 34-year period) were further extrapolated to predict the regional urbanization up to 2048 (i.e. 2014 plus 34 years). To achieve this, we developed several scenarios. The first scenario applied FUM and assumed proximity to urban areas in 2014 as the key driving factor that influenced urbanization. The second scenario applied EUM. For both models LAY for the year 1981 (LAY_{o81}) that was used to model urbanization in 1980-2014, was substituted by LAY for the year 2012 (LAY_{o12}) (the most recent available image) although the distance to Moscow City, highways and water bodies were assumed constant. An alternative third scenario was based on the New Moscow Project (see Section 7.2.1) with its assumed intensive urbanization at the full territory of 1500km^2 neighbouring Moscow City in south-west direction and expanding to the boundaries of the Kaluga Region (Figure 7.2). Although the actual urbanization hotspots within the New Moscow are unknown, the probability of intensive urbanization inside the New Moscow boundaries in the coming decades is much higher than outside. We therefore assumed that the whole New Moscow territory will be urbanized over the next decades. However, we understand that this likely overestimates urbanization trends. Although the New Moscow Project concentrates urbanization within the defined boundaries, it does not restrict urbanization elsewhere in the region. We therefore combined the New Moscow zone with the urbanization elsewhere obtained from FUM as the final 'New Moscow Urbanization Model' (NMUM). Three urbanization 771m grid maps for 2048 under the alternative FUM, EUM and NMUM scenarios were thus developed.

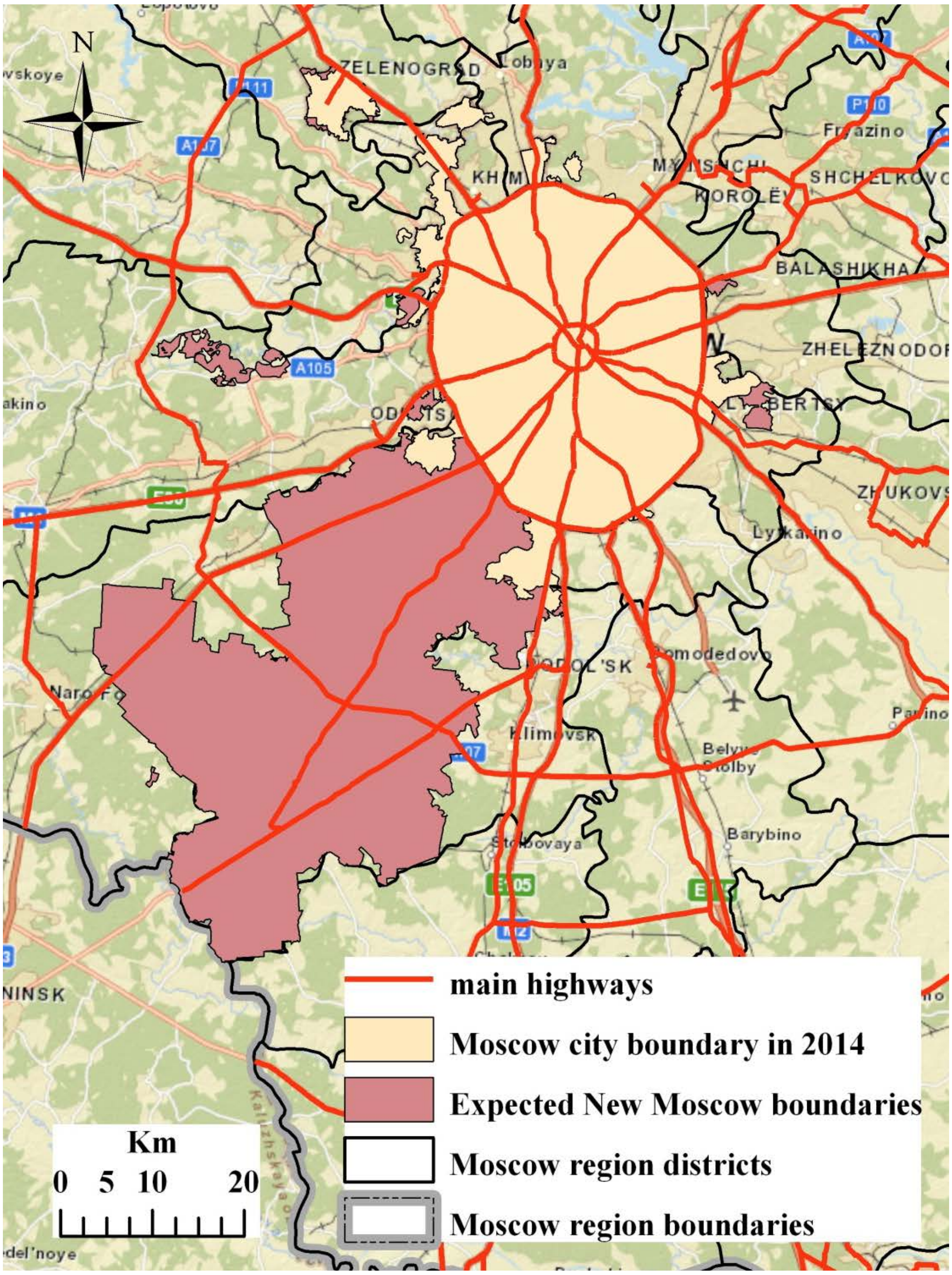


Figure 7.2 Projected allocation of the New Moscow

7.2.7 Estimating changes in SOC stocks resulted from urbanization between 2014 and 2048

Modelled urbanization trends in the Moscow Region under the three alternative scenarios were used to estimate possible negative and positive effects on net SOC stocks caused by urbanization. Vasenev et al. (2014) developed the region's 771m resolution grid maps for topsoil (0-10cm) and subsoil (10-150cm) SOC stocks. They calculated SOC stocks for three models, including only bioclimatic factors (i.e. soil type, relief, climate and vegetation), only urban-specific factors (i.e. functional zoning, soil sealing and settlement history) or both bioclimatic and urban-specific factors combined. We implemented the combined model, which was validated best. This model distinguished urban green areas and industrial and residential zones, and considered the percentage of local impervious areas (for a detailed methodology, see Vasenev et al., 2014b). To analyse changes in net SOC stocks, we compared average stocks per soil type (see Section 7.2.4) and aggregated land-use/land cover (LULC) types (e.g. forests, meadows, agricultural lands, urban lands or combined bogs and river plains). LULC was derived from the Land Cover Map for Northern Eurasia for 2000 (Bartalev et al., 2003) and depicted management conditions, whereas the zonal soil type maps referred to the soil capacity to store C, environmental conditions and distinct soil-forming factors. Five steps estimated the net effect of urbanization on SOC stocks:

The LULC map 2014 was combined with the actual urbanization map 2014 (see Section 7.2.3);

The LULC map 2014 was also combined to the alternative FUM, EUM and NMUM 2048 urbanization maps. This resulted in three LULC maps for 2048 (we focused only on land conversion into urban and ignored non-urban land-use change);

All resulting maps were joined with the soil layers (see Section 7.2.2). We assumed that the soil types remained constant for the study period;

Average topsoil and subsoil SOC stocks per combined LULC and soil type in 2014 and the three scenarios in 2048 were estimated using the Zonal Statistic routine in ArcGIS 9.3. The magnitude and spatial variability of SOC stocks in 2014 and 2048 were compared; and

Changes in SOC stocks that resulted from different scenarios per LULC and soil type were aggregated to estimate the net regional effect of alternative urbanization scenarios on topsoil and subsoil SOC stocks in the Moscow Region.

7.3. Results

7.3.1 Spatial patterns of urbanization in 1980-2014

Considerable urbanization occurred in the past 34 years the Moscow Region. The total urbanized area increased from 2139km^2 in 1980 to 2620km^2 in 2014. The urbanization was concentrated in the region’s central and south-western parts. The urbanization was strongly correlated with soil type. One-third of the newly urbanized territories were located on Orthic

Podzols and two-thirds on Eutric Podzoluvisols. However, urbanization was relatively higher on Orthic Podzols, where 1.4% of the area was urbanized compared to 1.1%, 0.6% and 0.2% on Eutric Podzoluvisols, Dystric Histosols and Orthic Luvisols respectively. No urbanization was observed on agricultural Luvic Chernozems, which cover only 0.5% of the region. As far as we can judge based on the initial LULC map, urbanization most likely occurred on forest and agricultural land – 41.0% and 46.0% respectively.

7.3.2 Spatial modelling of urbanization in 1980-2014

Both the FUM and EUM models effectively explain the urbanization patterns. The urbanization threshold was estimated based on the actual urbanization map and resulted in 0.98 and 0.72 for FUM and EUM respectively. The high FUM value is explained by the high model's accuracy and by the dominant effect of the neighborhood factors. This results in the proper allocation of newly urbanized areas in the buffer zone of existing urbanized areas. FUM gave 91.3% correct predictions and explained more than 74.0% of total variability (i.e. R^2; Table 7.2).

Table 7.2 Summary of the logistic regression models

Variable	FUM		EUM	
	B	Wald	B	Wald
Constant	0.91902	18.221	3.15074	424.023
LAI_{o81}	-0.04591	36.993	-0.06289	151.412
Elevation	-0.00555	22.365	-0.00654	65.801
Slope	-		-0.13880	70.708
Soil 1	0.70318	72.968	0.76398	174.868
Soil 3	1.15300	37.896	1.29595	114.159
Moscow_d	-0.00003	564.592	-0.00003	1068.664
Water_d	-0.00003	65.651	-0.00003	119.998
Highway_d	-		-0.00005	129.600
Neighb_1km	20.62336	2056.245	-	-
	Model parameters			
n	13685		13685	
Nagelkerke's R^2	0.743		0.370	
PCP	91.3		77.9	
Urbanized extent in 2014 (km^2)	2685		2659	

All selected variables were significant with p-levels < 0.001. Among the environmental factors, elevation and LAIo81 gave consistent negative effects on urbanization and soils gave positive effects. Socio-economic drivers also show significant influences on urbanization with p-levels <0.05. Negative relationships were obtained for the distances to Moscow City and water bodies. As expected, a strong positive effect was found for the 1km neighborhood factor, which dominated all other factors. This dominant effect is clearly reflected in the 2014 FUM map, where the majority of urbanized areas is located in the buffer zones of the 1980 urban areas (Figure 7.3A). Exclusion of the 1km neighborhood factor decreased the regression's accuracy and increased the amount of drivers considered. The percent correct predictions and R2 were, however, substantially lower than for FUM, but still relevant compared to other regional urbanization models (Li et al., 2013). Elevation, slope and LAIo81 showed significant negative relationships with urbanization. Socio-economic factors also negatively influenced urbanization with maximal Wald statistics obtained for the distance to Moscow City (Table 7.2). The resulting 2014 urbanization map showed a very centralized allocation of newly urbanized areas with the majority located east from Moscow City, where the highways are dense and the relief is more level than elsewhere in the region (Figure 7.3B).

7.3.3 Spatial modelling of urbanization in 2014-2048

Mapping results of the three alternative future urbanization scenarios do not only differ in total extents of urban areas but also in their spatial distribution. EUM shows the lowest level of urbanization with 2834km^2 of which the majority is located east from Moscow City, within 35-40km from the city boundary (Figure 7.4B). Forests, arable lands and river plains and bogs are the main land categories that are converted to urban with 332, 195 and 102km^2 respectively. Bogs and river plains are most influenced by urbanization – 18% of their area is converted to urban. FUM yielded 3302km^2 of urban lands in 2048. This scenario simulates urbanization to occur close to the existing settlements (Figure 7.4A). Urbanization results in depleting 264 km^2 forests and 228km^2 arable lands (respectively 1.1 and 1.6% of the region). Compared to the initial extent, river plains and bogs lost the largest (6.7%) area mainly in the north, east and central parts of the region. NMUM showed the highest urbanization (i.e. 4745km^2) with an obvious bias in the south-western locations from Moscow City where New Moscow is planned (Figure 7.4C). Most of the urbanized areas are converted from forests and arable lands – 1193 and 649km^2 respectively. Meadows and bogs, and river plains that are converted (112 and 48km^2 respectively), also contribute considerably. Land losses under NMUM are the most equally distributed between arable lands, forests and meadows loosing 4.7, 4.5 and 3.7% of their initial areas respectively. The largest conversion is again for bogs and river plains, losing in total 8.5%. This can be related to the scarcity (i.e. 1.2% of the total extent) of this landscape in the region (Table 7.3).

7.3.4 Estimating changes in SOC stocks under different urbanization scenarios

The urbanization scenarios for 2048 range from 500 to almost 2000km^2 of new-urbanized areas and corresponding loss of forest and arable lands in the Moscow Region. The negative effects of urbanization involve the 9.0 TgC emissions (1.9 and 7.1 TgC from the topsoil and subsoil respectively). These estimates assume that forests and arable lands are converted to impervious land. However, positive effects that are related to higher SOC stocks in urban soils compared to their natural counterparts are observed as well. The net effect of urbanization varies for different locations and soil layers.

The FUM scenario showed a slight net increase of 0.08 TgC in topsoil for the whole region. This is explained by opposite trends for different soil types. The Eutric Podzoluvisols (the poorest in topsoil C in the region with an average of 2.6 kgC m^{-2}) considerably increase its topsoil SOC stocks to 0.16 TgC, whereas Orthic Podzols, Dystric Histosols and Eutric Luvisols loose respectively 0.03, 0.04 and 0.002 TgC. We do not find large changes in topsoil SOC stocks for Luvic Chernozems. The total SOC stocks for urban areas increase for all soil types, whereas forests and agricultural lands loose up to 0.50 TgC. The EUM scenario results in a total loss of 0.16 TgC from the topsoil. A decline in SOC stocks is found for all soil types, except the Orthic Luvisols and Luvic Chernozems, where urbanization is rare. The specific distribution of new simulated urbanized areas results in a slight decrease of urban areas in Eutric Podzoluvisols. This ‘un-urbanization’ is rather unlikely and probably results from excluding the neighbourhood factor in UEM. The increase of SOC stocks in urban soils is compensated by C depletion in forests and agricultural lands in Orthic Podzols. SOC stocks increase in forests and agricultural lands, and urban areas on Dystric Histosols and Eutric Luvisols . However, these changes are not statistically significant. In contrast to the other two scenarios, the NMUM scenarios results in an increase of topsoil SOC stocks with 1.00 TgC. This is mainly caused by a consistent increase of 1.09 TgC in Eutric Podzoluvisols, where almost half of the urbanization occurs. All the other soils are depleted with approximately 0.03 TgC. Similar to FUM, an increase of SOC stocks in urban areas results from depleting forests and agricultural lands (Figure 7.5).

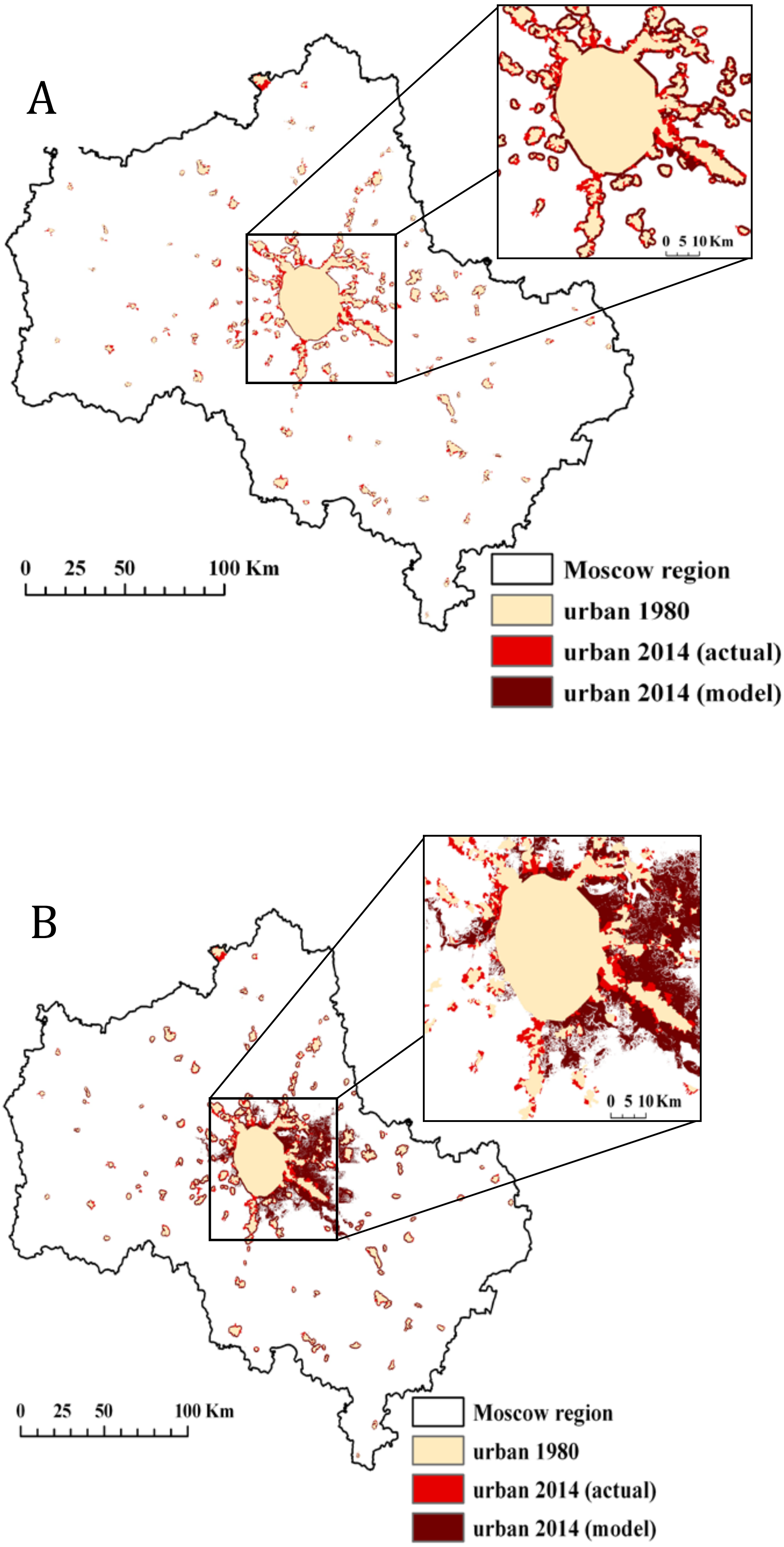


Figure 7.3 Modelled 2014 urbanization, based on FUM (A) and EUM (B)

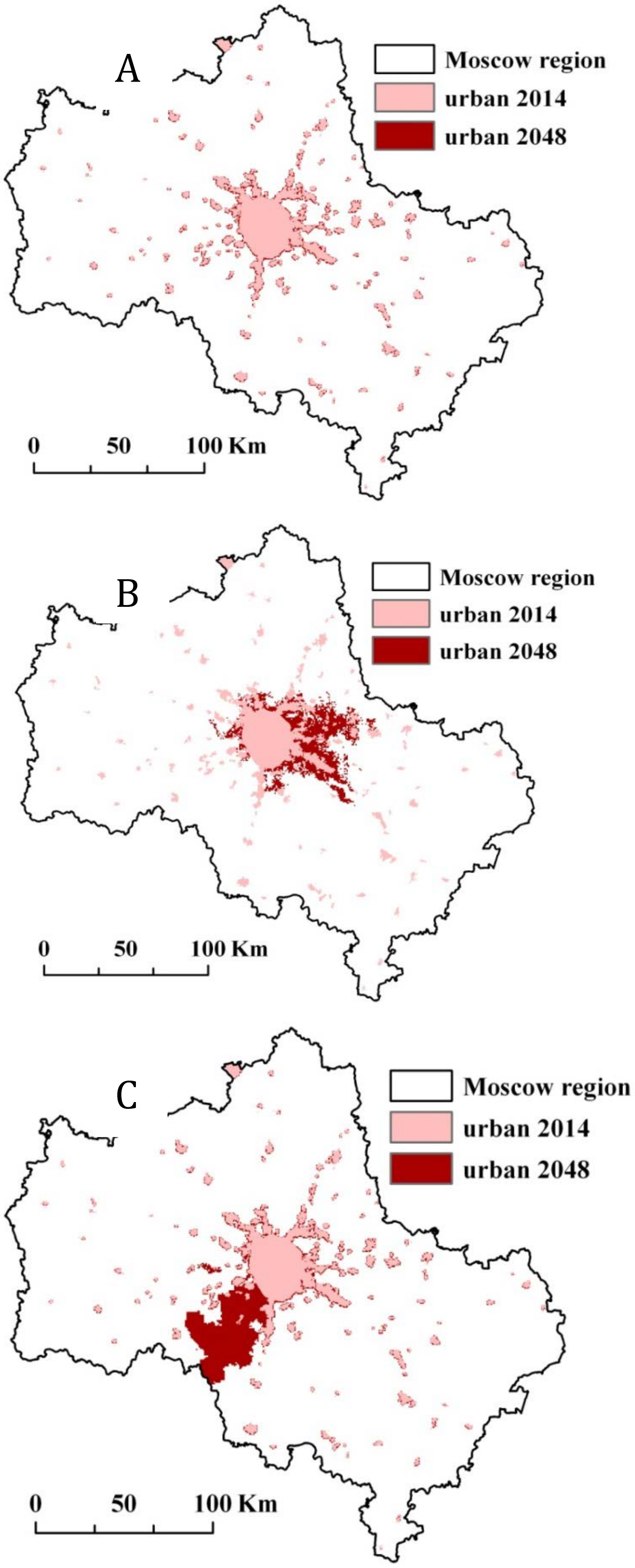


Figure 7.4 Modelled 2048 urbanization, based on FUM (A), EUM (B) and NMUM (C) scenarios

Table 7.3 Areas (km^2), occupied by forest (F), meadow (M), bog and river plain (B), urban (U) and agricultural (A) lands in 2014 compared to modelled in 2048 under different urbanization scenarios (delta (%) reflects land dynamic in 2014-2048 per LULC category)

Zonal soil type	LULC	Area 2014	FUM		EUM		NMUM	
			Area	Delta	Area	Delta	Area	Delta
Podzols	F	6290	6178	-108	5834	-452	6176	-110
	M	433	429	-7	372	-65	428	-8
	B	268	248	-23	183	-88	248	-24
	U	976	1204	228	1879	902	1209	233
	A	2175	2084	-91	1876	-299	2082	-93
Podzoluvisols	F	16723	16646	-163	16904	96	15742	-1067
	M	2004	2016	-11	2037	10	1925	-102
	B	155	144	-11	150	-5	136	-20
	U	1744	2060	309	1526	-225	3466	1715
	A	8739	8660	-127	8910	124	8258	-529
Luvisols	F	135	135	-2	139	2	135	-2
	M	188	194	0	194	0	194	0
	B	31	31	-1	32	1	31	-1
	U	35	41	6	27	-8	41	6
	A	1985	2013	-5	2022	4	2013	-5
Chernozems	F	7	8	0	8	0	8	0
	M	12	14	0	14	0	14	0
	B	8	8	0	8	0	8	0
	U	4	2	-2	2	-2	2	-2
	A	195	206	2	207	2	206	2
Peat and alluvial soils	F	1972	1975	-11	1991	5	1972	-14
	M	348	348	-1	339	-10	347	-2
	B	91	89	-4	81	-12	89	-4
	U	188	219	31	238	50	232	44
	A	1136	1129	-17	1111	-34	1122	-24

All three scenarios agree in a considerable net increase of subsoil SOC stocks in 2048. FUM reports a 4.11 TgC increase mainly originating from Orthic Podzols and Eutric Podzoluvisols (2.53 and 1.30 TgC respectively). Luvic Chernozems and Eutric Luvisols show slight increases in total SOC stocks by 0.03 and 0.24 TgC respectively, whereas changes in Orthic Luvisols are small. EUM shows a considerable increase in its SOC stocks of 10.00 TgC in the subsoil. The Orthic Podzols, where the original non-urban SOC stocks in the subsoil are limited and considerable urbanization occurs, are responsible for 90% of this increase. Finally, NMUM increases by 9.98 TgC. Orthic Podzols and Eutric Podzoluvisols again contribute most (2.57 and 7.06 TgC respectively). However, Luvic Chernozems and Eutric Luvisols also slightly increase. Again an increase in urban SOC stocks is compensated by depletion from forests and agricultural lands' losses. The forests loose more SOC stocks in Orthic Podzols and Eutric Podzoluvisols, whereas the agricultural SOC loss was higher elsewhere.

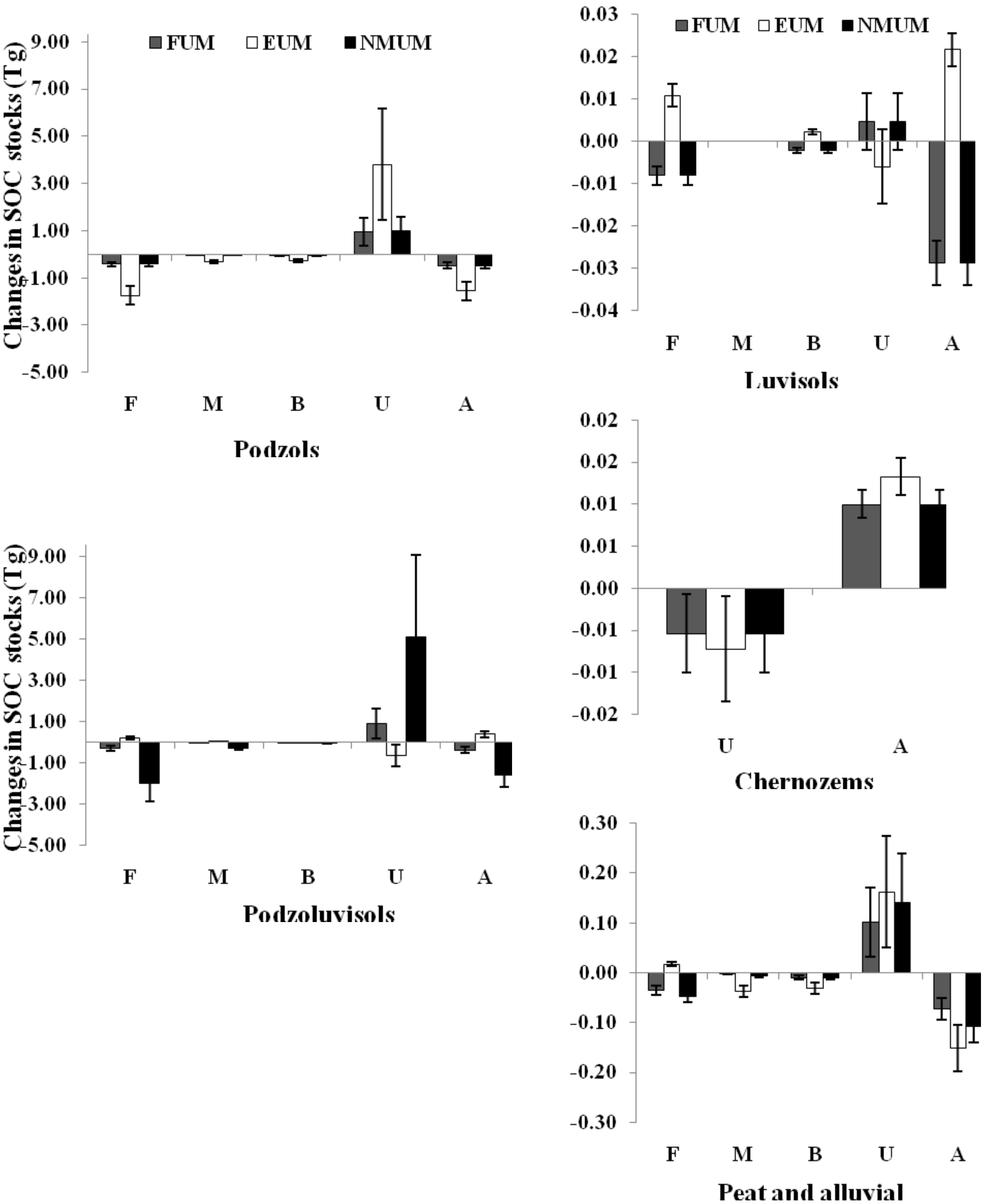


Figure 7.5 Changes in topsoils SOC stocks of forest (F), meadow (M), bog and river plain (B), urban (U) and agricultural (A) lands, located in different soil zones, resulted from alternative urbanization scenarios in the Moscow region

7.4 Discussion

7.4.1 Spatial patterns of urbanization in the Moscow Region

Ecological and social problems related to urbanization in the Moscow Region, recently concerned both researchers and politicians (Argenbright, 2008, 2011). This study is a first attempt to model current and future spatial patterns of urbanization as a function of environmental, socio-economic and neighbourhood driving factors, and to estimate their possible consequences on the regional SOC stocks. We found a negative influence of topography (i.e. slope and elevation) on the urbanization probability. This corresponds well with several other studies (e.g. Dubovyk et al., 2011; Ye et al., 2011) and is explained by additional costs of engineering, site preparation and construction in elevated and steep areas (Li et al., 2013). The Moscow Region, however, is rather plain. Therefore, topography has less overall influence compared to most other factors. The negative relationship with the distance to water bodies clearly shows that water bodies are attractive for urban development through the multiple recreational and aesthetical amenities, which settlers prefer. The negative relationship of distance to highways and to Moscow City is also coherent with previous studies, reporting that proximity to infrastructure and socio-economic centres enhance opportunities for education and employment, and thus increase attractiveness to settle (Luo and Wei, 2009; Poelmans and Van Rompaey, 2009). Considering that almost one third of the region's citizens are employed in Moscow City (Argenbright, 2008; IBM, 2011), proximity to the road network and city boundaries is critical. Neighbourhood is another important urbanization factor, especially in areas with a centralized structure such as Russia (Hu and Lo, 2007; Li et al., 2013). However, our 'backcasting' approach probably made this factor too dominant in our analysis. The resulting bias towards such neighbourhood factors motivated us to simultaneously test alternative urbanization scenarios (i.e. FUM, NMUM) and assess different urbanization patterns.

7.4.2 Scenario analysis of urbanization in the Moscow Region in 2014-2048

Our scenarios show a considerable future urbanization by 2048 varying from 8% (EUM) to 26% (FUM) and 81% (NMUM). This is in the same order of magnitude as reported recent urbanisation of 24% between 1989 and 2011 (Rosstat, 2012). Our analysis, however, was based only on 168 major settlements; small and new settlements since 1980 were ignored. Although our estimate is likely conservative, the predicted urbanization by FUM seems the most realistic. This is also confirmed by the statistical analysis, where the percent correct predictions and R^2 of FUM were significantly higher than the ones for EUM and NMUM. EUM likely underestimates urbanization. Less than 40% of its variability is explained and the scenario gives questionable urbanization patterns. This confirms the important role of the neighbourhood factor. NMUM clearly overestimates urbanization, but provides a valuable opportunity to estimate possible consequences of the New Moscow Project.

All three scenarios considerably alter land cover. Urbanization in the north and central parts of the region occurs mainly in forests, whereas in the southern part it occurs on fertile agricultural lands on Orthic Luvisols and Luvic Chernozems. EUM loses considerable forest areas on Orthic Podzols and Eutric Podzoluvisols, where most urbanization is projected. FUM results in more equal distribution of urbanization over the various soil types. This is explained by allocation of newly urbanized areas close to exciting ones independent on soil type. NMUM loses much agricultural lands that dominate the south-western part of the region where New Moscow is planned. The extent of bogs and river plains is reduced by 6% (FUM), 8% (NMUM) or 18% (EUM). Modelled urbanization loses on average 150-500 to 1000-1900km^2 of forests and agricultural lands under these three different scenarios. This land conversion can deplete various ecosystem services including SOC stocks.

7.4.3 Net effect of urbanization on SOC stocks under different scenarios

Although the observed net effect of urbanization on SOC stocks differs for each scenario, changes in topsoil SOC are always minor, whereas subsoil stocks increase. SOC stocks also increase in the soils with low fertility and slightly decline in more fertile soils. The slight changes in topsoil SOC stocks in FUM result from the homogeneous distribution of newly urbanized areas on among the soil types with different fertility and SOC stocks. EUM’s urbanization on Orthic Podzols and Eutric Podzoluvisols reduce topsoil SOC stocks. NMUM’s increase of topsoil SOC stocks result from the 1.1 TgC increase obtained in Eutri Podzoluvisols, where most urbanization occurs.

The influence of soil types is also evident for changes in subsoil SOC. Eutric Podzoluvisols and Orthic Podzols show the strongest SOC increases, whereas those in Orthic Luvisols, Luvic Chernozems and Dystric Histosols and Eutric Luvisols were small. The increase in subsoil SOC stocks for the different scenarios corresponds well with the predicted total urbanization extent and with the proportion of urbanization on Orthic Podzols and Eutric Podzoluvisols zone. NMUM projects the largest SOC increases.

No other comprehensive analyses of urbanization effects on SOC stocks (including both topsoil and subsoils) are published. This limits a proper verification of our results. However, some urban soil studies corroborate our findings. For example, most anthropogenic soil disturbances occur in top soil layers and cause soil quality, microbial activity and SOC stocks to decline (Gerasimova et al., 2003; Prokofyeva and Stroganova, 2004; Lorenz and Kandeler, 2005; Ivashchenko et al., 2014). Subsoil is less effected by such disturbances and can therefore accumulate SOC. Urban subsoil collects, for example, residential remains (e.g. coal, turf and wood), sewage and buried topsoil horizons (Stroganova et al., 1997; Lorenz and Lal, 2009; Vasenev et al., 2013). These typical urban horizons are usually referred as 'cultural layers' and can consist of 3 to 4% SOC (Alexandrovskaya and Alexandrovskiy, 2000; He et al., 2009; Dolgikh and Alexandrovskiy, 2010). The development of such cultural layers likely has a positive net effect on SOC stocks as was shown in our research. The variation in our SOC values also corresponds well with data from other studies (i.e. higher SOC under dry conditions and lower under humid conditions; Poyat et al., 2006). We included urban green zones into our analysis and predicted SOC stocks that are comparable to SOC stocks in lawns and urban parks (Svirejeva-Hopkins, 2004; Zircle et al., 2010). Our estimates are larger than studies that included only built-up areas (Pataki et al., 2006; Raciti et al., 2012). This shows the importance of a consistent definition of urban areas.

Obviously, our results provide no evidence for continued C-sequestration as a direct consequence of urbanization. To determine long-term changes in urban SOC stocks, the major C fluxes in and out urban soils (e.g. soil respiration and litter input) have to be assessed. Some local studies, for example, in the USA (Körner and Klopatek, 2002; Kaye et al., 2005) and China (Sun et al., 2009; Zhang el al., 2010) report on high SOC stocks and respiration in urban soils. Whether urban soils are a net C source or sink is difficult to determine. Our findings, however, contribute to better understand the effects of urbanization and show that under certain conditions urbanization can enhance SOC stocks.

7.4.4 Uncertainties in carbon change predictions

Regional spatial analysis of urban areas faces several problems. Major problems, for example, include the high variability over short distances and multiple interacting bioclimatic and anthropogenic factors (Vrscaj et al., 2008; Pickett et al., 2011; Vasenev et al., 2014). Several assumptions helped us to distinguish different urban areas, to develop the initial SOC stock map, to model and quantify urbanization trends, and to determine urbanization effects on SOC stocks. These assumptions, however, added uncertainties to our study. When implementing a 'backcasting' method to characterize urbanization trends, for example, we *a priori* ignored the establishment of new settlements that were remote from existing urbanization centres, and settlements smaller than 2km^2 due to the relatively poor accuracy of the 1980 map. Some recent developments are also excluded from our analysis (e.g. private cottage villages and summer residences, which are poorly tracked by federal censuses, have rapidly expanded over the last few years; Argenbright, 2011). Together the resulting uncertainties probably caused that the scenarios likely overestimate the future urbanized area. In NMUM, we assumed urbanization of the whole New Moscow area. However, the considerable investments in the New Moscow Project could slow urbanization activities elsewhere in Moscow Region.

The resulting changes of subsoil and topsoil SOC stocks are also not fully certain. The high variance in our results is probably amplified by lack of spatially explicit data on some urban areas' features, explaining SOC stocks (see Vasenev et al., 2014b). For example, the increase of subsoil SOC stocks due to urbanization can be explained by the cultural layers. However, the actual SOC quantity in these cultural layers is a combination of stocks brought by historical residential activities and buried natural soil horizons. The settlement history can vary within a city (e.g. four different historical districts exist in Moscow City; Vasenev et al., 2013c), but cultural layers would not be expected in new urbanized areas. Distinguishing between the historical and natural components of cultural layers was impossible with available methodologies. Therefore we used averaged urban subsoil SOC stocks. We also did not distinguish between various functional zones in urbanized areas and thus ignored the spatial structure of residential, recreational and industrial areas. Although these obvious uncertainties can question our results, our main findings are robust and relevant. There is clearly a considerable effect of urbanization on SOC stocks. This also corresponds well with previous studies and general background knowledge of SOC stocks and fluxes in urban soils.

7.5 Conclusions

Urbanization is a major trend world-wide and regionally it is a key factor of land dynamics and environmental change. We showed considerable urbanization in the Moscow Region over the last decades as a function of social, economic and environmental driving factors. Extrapolation of obtained urbanization patterns to three alternative future scenarios resulted in an 8 to 81% increase of urban areas by 2048. Modelled urbanization caused remarkable changes in land cover from conversion of approximately 2000km^2 of forests, arable lands and wetlands into urban areas. Although many studies claim a neutral or negative impact of urbanization on SOC stocks (e.g. Nilsson et al., 2000; Schaldach and Alcamo, 2007; Schulp and Verburg, 2009), we clearly showed a small but positive net effect on SOC stocks in the Moscow Region. This finding results from a considerable increase in subsoil SOC stocks resulted from conversion of natural soils that store little SOC, into urban soils. The New Moscow Project scenario increased the SOC stocks in topsoils and subsoils most.

Land-use change in Russia and in the Moscow Region specifically is to a large extent controlled by centralized political decisions. This gives studies as ours a clear addressee, as we explored and modelled future trends in urbanization patterns and their SOC consequences in the Moscow Region. We highlighted that urban areas possess substantial opportunities to capture and even enhance SOC stocks and thus mitigate climate change. This is probably also true for other environmental issues (e.g. enhanced net primary productivity of urban forests; Nowak and Crane, 2001; nitrogen deposition; Raciti et al., 2008 - and acidity neutralization in urban soils; Gerasimova et al., 2003). This optimistic conclusion should be further explored by land-use planners and scholars worldwide, since urbanization will be progressively more important in the future.

Acknowledgements

The project was partly supported by the Wageningen University Sandwich PhD Fellowship Program, Governmental Grant # 11.G34.31.0079 and the Russian Foundation for Basic Research, project # 14-04-31901 and 15-54-53117. The authors thank Prof. Igor Savin and Dr. Daniil Kozlov for providing secondary data, Julia Sotnikova and Dmitry Sarzhanov - for the assistance with chemical analysis Prof. Ivan Vasenev and Dr. Nadezhda Ananyeva for valuable suggestions and useful comments.

8 SYNTHESIS

8.1 Introduction

Although urban areas occupy less than 3% of the global land area, they often exceed 10% in regions with high population density. In addition, urbanization occurs at a rapid and still increasing pace and its influence on natural and human environments is not confined by the settlements' boundaries. Urban ecosystems are unique in terms of vegetation and soils. Urban soils are formed under specific conditions of urban environments and anthropogenic processes influence their functions and services. Traditional views of urban ecology stress that urban soils mostly experience anthropogenic disturbances and threats, including soil pollution, sealing, compaction and depletion of soil fertility. However, the capacity of urban soils to perform important functions and provide ecosystem services, like carbon sequestration, is still poorly known. Most global and regional carbon assessments ignore urban soils, whereas many local studies report a considerable potential of urban soils to both sequester and emit carbon. Urbanization is one the main factors that influence the carbon balance of soils in an urbanized region and thus contribute to either accelerating or mitigating climate change.

An analysis of soil organic carbon (SOC) stocks in urban environments is needed to understand the consequences of urbanization on the carbon balance. So far this information is rare due to high heterogeneity of urban areas and methodological constrains. In the thesis I addressed the methodological constrains by adapting advanced approaches to analyze spatial and temporal variability of SOC stocks to urban environment and bioclimatic conditions of the Moscow region. I analyzed and quantified the effects of urbanization on SOC stocks in Moscow Region. The analysis was guided by four research questions (RQs), all applied to Moscow Region:

RQ1 What are the impacts of soil type, land-use type, settlement age and depth on SOC stocks?

RQ2 How variable are SOC stocks in urban soils and does inclusion of urban soils improve the regional SOC stocks' assessments?

RQ3 How does urban soil's respiration and its spatial variability differ compared to those in non-urban areas?

RQ4 What are the net effects of future urbanization on the regional SOC stocks?

Intensive soil surveys were conducted in different land-use types of the Moscow Region to answer RQ1. Measured SOC concentrations were used to develop a digital SOC map of the region, addressing RQ2. Soil respiration from urban lawns was monitored and compared to the adjacent forest and cropland sites regarding temporal dynamics and spatial variability. A standardized basal respiration was tested and implemented to analyze spatial variability of soil respiration in the Moscow region, addressing RQ3. Finally, the net urbanization effects on SOC stocks were modelled for several alternative scenarios to answer RQ4. The answers to the four research questions are presented and discussed in Sections 8.2 and 8.3, focusing on the role of urban soils in the regional carbon balance of the Moscow Region, while addressing the uncertainties and methodological constrains of these answers. Sections 8.4 and 8.5 question the traditional view on urbanization as a disturbance or threat for soil functions and present my findings in context of a sustainable city concept. Section 8.6 synthesizes all RQs into the overarching findings, presents the innovative aspects of this thesis and puts the findings in a broader perspective, showing that the methods developed and the insights obtained for the unique Moscow Region likely are also applicable for other regions in the world.

8.2 The role of urban soils in the Moscow regional carbon balance

The Moscow Region is a vivid example of rapid urbanization. Urban areas in the Moscow Region have recently clearly expanded and this has influenced soil properties and functions far beyond the legal Moscow City boundaries. Therefore, studying the urban soils in the Moscow Region in necessary to understand carbon stocks, fluxes and their spatial variability.

Most of the previous carbon assessments in Russia, including those for the Moscow Region either ignored urban soils or valued their role as negligible (e.g. Isaev and Korovin, 1995; Shvidenko and Nilsson, 1998; Romanenkov et al., 2007; Smith et al., 2007). I conducted an intensive soil survey over different land-use and soil types in the Moscow Region and clearly demonstrated higher SOC concentrations in urban soils compared to non-urban ones for different soil types (Figure 3.2) and in average for the region (Table 3.3). Urban SOC concentrations surpassed significantly the concentrations in non-urban areas for the mixed subsoil layers (10-150cm). This difference probably resulted from the contribution of the “cultural layers” storing considerable amount of carbon (He et al., 2009; Dolgikh and Alexandrovskiy, 2010). This finding is even more evident when estimating SOC stocks. SOC stocks in urban soils were on average larger than for any other land-use and up to 90% of carbon contained in subsoils (Figure 4.5). These results are in good agreement with other local studies (e.g. reported by Qian et al., 2002; Zircle et al, 2011; and reviewed by Lorenz and Lal, 2009), which claim high SOC concentrations and stocks in urban soils compared to forests and agricultural soils and relate this surpass to the influence of anthropogenic factors.

However, any conclusion on the capacity of urban soils to store carbon should consider the respiration of urban soils as an important carbon efflux. There is no agreement between the magnitude of respiration from urban soils and natural soils ones in literature. Global databases usually lack this data (Houghton, 2003a; Bond-Lamberty and Thomson, 2010) and regional and local research sometimes report contrary outcomes. Some studies show low respiration in urban soils as a result of unfavorable conditions for microbes and permanent anthropogenic disturbances (Lysak et al, 2010; Ivashchenko et al., 2014). However, many other studies (Jo and McPherson, 1995; Bandaranayke et al., 2003; Sarzhanov et al., 2015) claim urban soils' respiration as comparable to natural soils or surpassing them. This is explained with the higher SOC stocks usually reported for urban soils (Pouyat et al., 2002; Zircle et al., 2011), often amended with artificial organic substrates (e.g. compost and sewage materials) during soil reclaiming and greenery work (Lorenz and Lal, 2009; Beesley, 2012). These stocks are rich in labile forms of SOC, which can be more easily mineralized by microorganisms. Less is known about an influence of the other factors of an urbanized environment (e.g. urban climate, introduced plant species and anthropogenic sediments in parent material) on urban soil's respiration.

I found a high variability in respiration of urban soil in space and time as the result of monitoring at the test area in Moscow city. Substantial fluctuations in urban soils' respiration were mainly driven by diurnal and seasonal changes in soil temperature (Figures 5.3 and 5 4). Soil moisture effect was also significant for the cropland site. Although temporal variability was high, average soil respiration from urban lawns surpassed one from non-urban sites (Figure 5.4). This illustrates the important role played by urban areas in spatial variability of soil respiration, which was also indicated by my ANOVA results (Table 5.6). The observed spatial variability likely resulted from different responses of soil respiration to anthropogenic disturbances (also depending on the measuring approach).

In situ measurements of soil respiration at the test area in Moscow city gave higher values in urban lawns, compared to croplands and urban forest sites. Moreover, the most disturbed lawn presented the highest respiration (Figure 5.6). However, the basal respiration measured at the standard conditions showed the opposite trend with lower values in urban sites, compared to undisturbed forest (Figure 5.7). A different response for in situ and standardized basal respiration results illustrates the underlying mechanisms of both indicators. In situ soil respiration is sensitive to dynamic of soil temperature, moisture and especially to the anthropogenic pressure (Rey et al., 2002*;* Kaye et al., 2006*;* Kurganova, 2010). Basal respiration is likely a function of more stable soil chemical features and prolonged anthropogenic influence (Ananyeva, 2003; Vasenev et al., 2012). In situ respiration characterizes the short-term disturbance effect, whereas basal respiration refers to the potential carbon efflux by soil microbes. High *in situ* respiration combined with low basal respiration defines urban carbon stocks as unstable, since an actual carbon efflux is above the potential of soils to emit carbon, determined by soil microbiological activity.

I showed that more carbon was contained in urban soils than in non-urban soils in the Moscow region, and also their potential to emit carbon is higher. However, my findings do not prove whether urban soils are carbon sinks or sources. One of the main reasons for this uncertainty is the high spatial heterogeneity in urban soils and their carbon stocks and fluxes as affected by bioclimatic and management factors. Spatial heterogeneity is probably one of the most typical features of urban soils. For all analyzed features (e.g. SOC concentrations, SOC stocks, in situ soil respiration and basal respiration) spatial variability (i.e. expressed through variance coefficient) in urban soils was 40-60% higher compared to the natural counterparts (Tables 3.3, 4.6 and 5.3-5.5). Moreover, spatial variability was in good agreement with the level of disturbance with the highest variability shown for the most disturbed sites (i.e. industrial area) (Figures 4.5 and 5.5). This finding is vividly illustrated by the developed maps of SOC stocks and BR in the Moscow Region (Figures 4.4 and 6.2) and especially by the maps of the variance coefficients (Figures 4.6 and 6.3). Urban soils contributed to the natural soil heterogeneity at the region with more homogeneous southern part occupied by Orthic Luvisols and Luvic Chernozems and patchy eastern part, covered by combinations of Dystric Histosols and Eutric Podzoluvisols. Inclusion of urban soils into analysis resulted in considerable increase in average variance coefficient (almost two times for SOC stocks and 30-50% for BR) with the 'hot-spots' strongly related to the settlement boundaries.

This thesis illustrates the high carbon stocks contained in urban soils and reports a remarkable potential of urban soils to emit carbon, especially as an instantaneous response to anthropogenic disturbances. It also illustrates that urban soils are the main contributors to spatial heterogeneity in regional carbon stocks and soil respiration. However, my findings do not fully explain the factors driving spatial-temporal variability of urban SOC stocks. Statistical analyses confirm the influence of soil type, depth and functional use on SOC concentrations (Table 3.4) and stress the dominant role of urban-specific factors compared to bioclimatic when influencing SOC stocks. However, my regional models explain only 10 to 30% of the total variance for SOC stocks (Table 4.6.) and 30 to 50% of total variance for basal respiration. Many factors influencing urban SOC stocks remain under-observed, contributing to high uncertainty of the obtained results. This uncertainty and its possible sources and consequences are further discussed in Section 8.3.

8.3 Quantifying urban SOC stocks' variability in space and time: uncertainties and methodological constrains

Urbanization effect on regional SOC stocks is likely uncertain. This uncertainty is coming from a range of factors, including i) complexity of the research areas and lack of legacy data, ii) methodological constrains in adapting digital soil mapping (DSM) to urban soils, iii) modelling assumptions, and iv) deviations in definitions of 'urban' areas. I faced uncertainty problems in major stages of the analysis. This uncertainty has been considered when interpreting the results. In this section I review possible sources of uncertainties and the possibilities to avoid it in future analysis.

The complexity of studied urban areas constrained implementing conventional techniques of soil survey and analysis of soil carbon stocks and fluxes, thus the methodology for the specifics of urban environment had to be adapted. Urban areas have a very diverse and patchy spatial structure, including a large number of small contrasting areas, mainly referring to different management conditions and functional zones (i.e. recreational, residential and industrial). Trying to analyze the factors influencing SOC in urban soils, I concentrated on sampling in urban areas, leaving large non-urban areas with low sampling densities. I obviously could not observe all 68 cities and towns in the region and only selected seven of them, representing different but characteristic environmental (climate, vegetation and soil type) and urban-specific (size, age, functional zones) conditions. Including more settlements into my analysis could better explain variability of climatic conditions, but would limit the understanding of SOC spatial variability within a settlement.

Soil sampling depth was another important methodological constrain. Two main issues are usually debated regarding sampling depth for SOC stocks' assessment, as it was reviewed by Minasny et al., 2013: i) whether to sample by layers or by genetic horizons, and ii) what depth to sample. When analyzing soil respiration and especially soil microbiological activity (i.e. basal respiration (BR)) the samples are usually taken by layers, because these parameters are very sensitive to depth and BR from the 0-10cm and 10-20cm layers, located within the same Ap horizon, can be significantly different as it was shown by Susyan et al., 2006; 2009; Ananyeva et al., 2008 for agrogenic Eutric Podzoluvisols at the cropland sites and Luvisols in the forested area of the Moscow region. Soil sampling by layers was chosen for the aim of the thesis, considering the following arguments: i) SOC concentrations and BR were measured at the same samples, since the relation between parameters was studied and BR was used as a proxy to map soil respiration, which in its turn was used to illustrate SOC stocks' temporal dynamics; ii) measuring SOC and BR from a single sample also optimized the costs, which was essential for my sandwich PhD project. Conventional sampling in soil pits with samples from genetic horizons was difficult to implement in urban areas due to the high costs and organizational constrains (e.g. with obtaining official permission for soil excavation in a city). Besides described urban soil profiles are very diverse and general classification is still lacking (Rossiter, 2007; Prokofyeva, 2011; 2013).Therefore, pragmatic choices had to be made: sampling a composite sample for the topsoil and a single sample from the subsoil.

Topsoil was defined as 0-10cm layer, which corresponds with many traditional regional and global carbon surveys (FAO, 2001; Nilsson, 2002; Kudeyarov et al., 2007; Zhang et al., 2011) and researches on soil microbiological activity (Ananyeva, 2003; Lorenz and Kandeler, 2005; Ivashchenko et al., 2014). Defining subsoil depth was less straightforward. Many researches on SOC stocks and especially on BR ignore subsoil layers (Mishra et al., 2010; Gavrilenko et al., 2011; Martin et al., 2011), however I aimed to investigate subsoil's contribution to SOC stock and soil respiration. Two sampling strategies in terms of subsoil depth were chosen: i) mixed samples 10-150cm were taken, when regional variability in SOC stocks and BR was analyzed (Chapters 2, 3, 6, 7 and 8); ii) mixed samples 10-40cm were analyzed to compare spatial variability in soil respiration captured by direct and indirect approaches (Chapter 5). Obviously, aggregating 10-40cm and 10-150cm subsoil into a single sample approximates only rough results, especially for the basal respiration that is known to be very sensitive to soil depth. However, this aggregation gave us an opportunity to estimate on the contribution of the subsoils to total carbon stocks, their variability and dynamics that is often left out of regional analysis, as it was discussed in Chapters 4 and 6. Subsoil is a very important carbon stock and a potential source of soil respiration in urban areas, as it was clearly shown in Chapters 3 to 6.

One of the main challenges of my thesis was to adapt the DSM technique for the spatial analysis of SOC stocks and soil respiration, when shifting from the local to the regional analysis in the very urbanized Moscow Region. Several assumptions enabled implementing

DSM in urban areas but added to the uncertainties in my study. For example, I could not distinguish between industrial and residential zones based on the available satellite images and assumed for them similar soil sealing, although the field data showed significant differences in SOC and BR between them. The age factor, influencing subsoil SOC stocks, was taken constant for the whole settlements, since the spatial data on older and younger districts was not available for majority of the settlements.

The uncertainties of the spatial SOC stocks' analysis increase when temporal dynamics of SOC stocks was studied. Conventional comparison between the present SOC stocks with ones measured in the past was not possible due to high heterogeneity of the research area and limited data, available for research plots in the past. Therefore, the main focus was given to soil respiration as the main carbon efflux from soil to the atmosphere and consequently an important parameter to illustrate temporal dynamic of SOC stocks. Soil respiration *per se* is highly variable in time. This was considered by diurnal and seasonal monitoring carried out for the test area. Since continuous 24-hours measurement was not possible for my large number of sample points, I addressed temporal dynamics by averaging soil respiration for three hours (diurnal dynamics), ten days (growing season) and 30 days (cold season). Although the methodology is often used, when large number of observation points constrained possibility for continuous 24-h measurements types (Rey et al., 2002; Larionova et al., 2005; Castaldi et al., 2008; Kurganova et al., 2011), it still yields in substantial uncertainty, since many fluctuations (including 'short-term' fluctuation from anthropogenic disturbances) may be ignored.

Considering high spatial variability shown for *in situ* soil respiration, BR was used as a reliable proxy for analyzing and mapping soil respiration at the regional scale. Mapping BR as a spatial proxy for soil respiration was another assumption taken. BR doesn't provide information on the actual carbon outflow but refers to the potential of soil microbes to emit carbon. Factors, influencing BR and in situ respiration may differ, as it was shown for the test area in Moscow City, where both approaches were compared (Chapter 5). However, implementing BR as a spatial proxy of soil respiration enabled expanding research area and estimated regional spatial variability of a potential carbon efflux. This was novel for the Moscow Region and urbanized regions in general.

Finally, some uncertainty could come from deviations in 'urban' definitions in Chapters 3 to 7. When analyzing SOC concentrations in urban and non-urban areas of the Moscow Region (Chapter 3) I considered only open areas within the legal city boundaries and paid no attention on the impervious areas. This could cause considerable overestimation when extrapolating from the point data to regional estimates of SOC stocks. Thus both open and impervious areas were taken into account in the spatial analysis of SOC stocks (Chapter 4) and basal respiration (Chapter 6). Although samples were taken only from non-sealed soils, the percentage of sealed areas was considered for different functional zones (residential/industrial and recreational) and included into analysis. When modelling urbanization in Chapter 7, the same criteria were kept and urban areas were defined as a combination of multiple functional zones (i.e. recreational, residential and industrial), including both impervious (built-up zones, roads, commercial land) and open areas (green zones, parks, lawns) located within the legal urban settlement boundaries.

Analyzing the spatial-temporal variability of soil carbon stocks in urban areas is a challenging, but interesting and important task. In the thesis a novel methodology for such analysis was presented. Specifics and complexity of urban areas, variability of SOC stocks in space and time forces us to take several assumptions. This helped to answer RQs 2 and 3, but increased the study's uncertainty. Likely, this was an 'unavoidable price' for extrapolating local results to the level of the highly urbanized region. Although the uncertainty is high, obtained spatial trends of SOC stocks in the region are robust and the important role of urban soils in regional carbon stocks is clear. These outcomes are critical to model urbanization effect on carbon stocks and to understand whether urbanization is a threat or an opportunity for carbon sequestration as discussed in Section 8.4.

8.4 Urbanization as a threat and an opportunity for carbon sequestration

Although urbanization is increasingly important, its environmental consequences in terms on carbon sequestration in soils are still poorly known. Historically urbanization was mainly studied as a potential soil threat, resulting in contamination, over-compaction, sealing, biodiversity depletion and alteration of temperature and water regime (Stroganova et al., 1997; Lysak, 2000; Kurbatova et al., 2004; McKinney, 2006). Many regional and global studies though ignore urban soils or consider neutral or negative effect of urbanization on carbon stocks and fluxes (Elvidge et al., 2004; Stroganova et al., 1997; Schulp and Alcamo, 2009). This places urbanization among the major threats for carbon sequestration in coming decades, since remarkable urbanization is expected by 2050 worldwide and considerable urban expansion will occur on the areas covered by soils with high carbon contents (Svirejeva-Hopkins et al., 2006; Seto et al, 2011). However, recent studies highlight the potential of urban areas to provide and support important ecosystems services and soil functions, such as enhancing carbon storage (Lorenz and Lal, 2009; Raciti et al., 2008; Morel et al., 2014). In Chapter 7, I modelled the net effect of urbanization on SOC stocks in the Moscow Region for alternative urbanization scenarios, addressing RQ4.

Based on the most plausible scenarios a considerable 26% to 81% urbanization is expected in the Moscow Region in coming decades. Such a remarkable urbanization occurs mainly on forest and agricultural lands and has both positive and negative impacts on soil carbon stocks. Negative impact is caused by soil sealing and excavation, whereas positive impacts result from formation of new urban soils, containing larger amount of carbon, coming from added artificial composts and turf substrates and stored in cultural layers. The net effect of urbanization on carbon stocks is determined by the equilibrium of the negative and positive impacts. This equilibrium will likely depend on pre-urban land-use type and soils and on the structure within new urbanized areas, including different functional zones. An allocation of new urbanized areas depends on environmental, social-economical and neighborhood factors. Topsoil and subsoil should be analyzed separately since a different urbanization effect can be expected. A conceptual model of urbanization effect on soil carbon stocks can be illustrated by the scheme on Figure 8.1.

For the case of the Moscow Region a clear positive net effect of urbanization on soil carbon stocks is found. This is mainly determined by an increase of SOC stocks on soils with low fertility, i.e. Eutric Podzoluvisols and Orthic Podzols. Up to 90% of the increase in SOC stocks takes place in the subsoil. On the more fertile Orthic Luvisols and Luvic Chernozems the positive effect on SOC stocks is minor and even slight decline is observed. Considering that up to 70% of the Moscow Region is covered by Eutric Podzoluvisols and Orthic Podzols, a positive net effect of urbanization is plausible. Obtained correlation with natural soil types highlights urbanization as an opportunity for carbon sequestration in areas with poor soils globally, including boreal and arid climatic zones. However, in humid areas with more fertile soils, a positive net effect of urbanization can be negligible or even a negative effect can be expected.

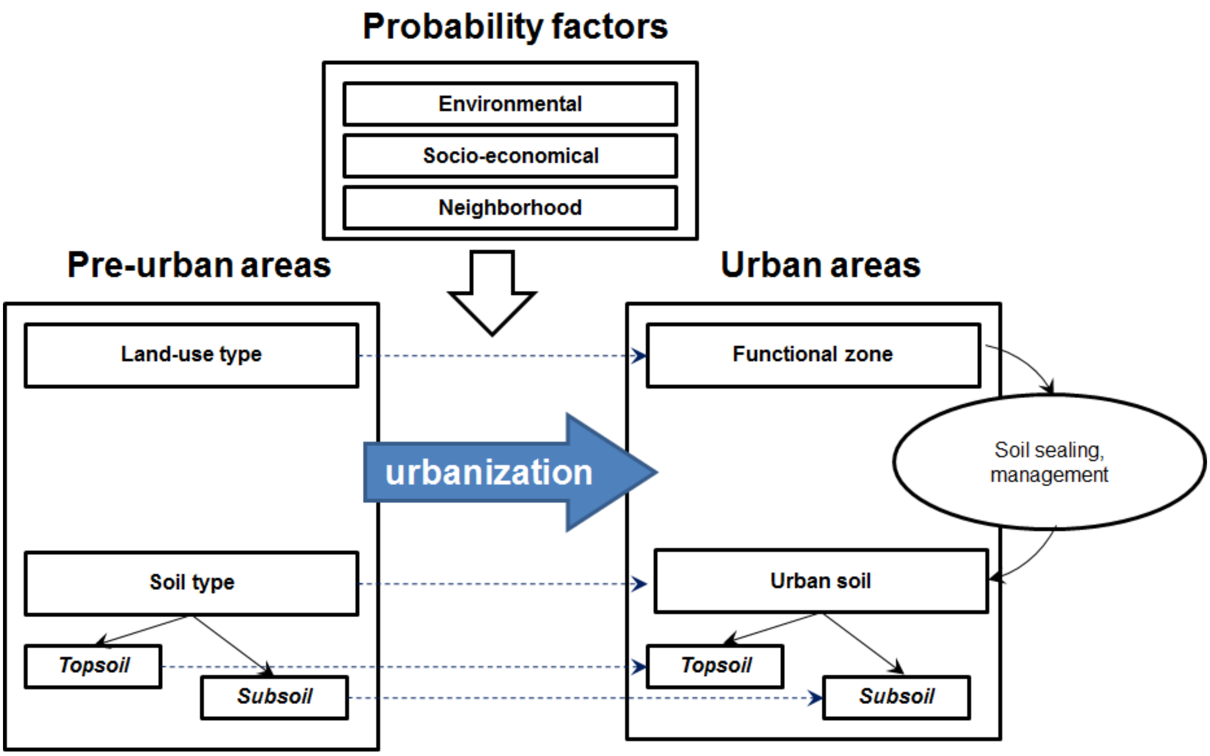


Figure 8.1 Conceptual model on urbanization effect on soil carbon stocks

Considering the different effects of urbanization for different bioclimatic and soil conditions, land-use planning within a new settlement can become a key driver to enhance carbon stocks or minimize carbon emission. Unfortunately, I could not distinguish between functional zones in future urbanized areas in the Moscow Region due to data scarcity and thus ignored this important driving factor (Chapter 7). However, the findings reported in Chapters 3 to 6 confirm a strong effect of functional use and land management on carbon stocks and soil respiration in urban soils. This effect shall be taken into account when planning a settlement structure i.e. allocating new residential blocks or green zones. Considering maintaining soil functions and services, including carbon sequestration, should be among the key factors, driving the decision-making in urban planning of a new, so-called 'sustainable' city. In future perspective moving urban planning towards sustainable cities will allow taking urbanization as an opportunity for carbon sequestration, rather than a threat for soils and environment.

8.5 Urban soils in context of a sustainable city

Urban ecosystem is a relatively new ecological phenomenon. The first archeological settlements, recognized as towns, date back to eight to ten thousand years ago. The first megapolis with the population over one million – the city of Rome – achieved this threshold in the first century BC during the Julius Cesar reign (Denisov et al., 2008). Only 16 cities in the world exceeded one million citizens by 1900. However, this number rapidly increased to more than 400 at the beginning of the 21st century (Berry, 2008). Urban ecosystems are the most artificial compared to agricultural and natural systems. They are driven by humans and for humans and anthropogenic factors have a predominant influence on such urban environments. These drivers allows developing convenient and comfortable conditions for citizens, but as a drawback, sustainability of urban ecosystems and their components (air, water, vegetation and soil) strongly depends on the decisions taken by humans, for example, through urban planning.

Historically, cities were planned mainly to support military defense, industry and trade, which is vividly illustrated by ring and sector structures of Moscow and London (Denisov et al., 2008) or block structure of New York (Pickett et al., 2011). With increasing industrialization this urban planning strategy resulted in multiple social and environmental problems, including soil, water and air pollution, waste disposal and traffic congestion. These problems constrained the quality of life in cities and created unfavorable conditions for residence. In result, new ecological concepts of urban planning were developed, starting from the second half of the 20th century (Jacob, 1961; McHarg, 1969; Bacon, 1969). These new concepts highlighted the role of 'green and blue spaces' (including parks, lawns, yards, gardens, rivers, streams and ponds), and the functions and services they provide to people (Gomez-Baggethun et al., 2013). Major attention was given to planning small functional zones, following ecological framework of patch dynamics in urban design (McGrath et al., 2007), rather than to a traditional master plan of the settlement as a whole. This tendency in urban planning is defined by Pickett et al. (2011) as a shift "from sanitary city to sustainable city". A sustainable city is a social-ecological ecosystem, resilient to anthropogenic and environmental stresses (e.g. climate change) and providing ecosystem functions and services (Pickett et al., 2011).

Urban soil has a great but still poorly studied and rarely used potential to play a key role in an ecosystem of a sustainable city. Currently, urban soils face a paradox of being of the highest value regarding property and building issue, and being almost totally ignored with regard to the functions and ecosystem services they can provide (Morel et al., 2014). According to the recent review by Morel et al. (2014) urban soils provide from 9 to 15 ecosystem services, depending on the surface features (sealed/ open) and anthropogenic disturbance (pseudo-natural or engineered). Urban soil's carbon stocks directly or indirectly relate to at least five of these services: food production, non-food biomass, global and local climate and biodiversity. My findings on local and regional spatial variability and SOC stocks can be a valuable background to support decision-making in a sustainable city planning. Local data on urban SOC stocks and soil respiration in different bioclimatic and management conditions can be used to develop sustainable constructions of urban soils to enhance carbon sequestration. Regional trends in SOC dynamic as resulted from urbanization should be considered when analyzing environmental consequences of the regional land-use change policies, including such ambitious projects as the New Moscow Project. My findings can have a very clear addressee in the Moscow Region, where building and reconstruction processes take place on hundreds of square kilometers each day and the consequences of rapid urbanization are still poorly investigated. They will get useful to many other cases worldwide, if future urbanization will get more connected to the sustainable urban planning.

8.6 Conclusions

My study clearly shows the multiple and versatile effects of urbanization on SOC stocks. I proved that urban soils can contain considerable amount of carbon. This is comparable to or higher than carbon stocks in natural soils. The evidences of high SOC stocks in urban soils were given before by local research in Germany (Lorenz and Lal, 2009), USA (Raciti et al., 2012) and China (Zhang et al., 2010). However, in the thesis this outcome was tested and confirmed for a variety of bioclimatic conditions and managements for the Moscow Region. This is novel and likely provides insights for other urbanized regions in the world.

Urban SOC stocks were presented as a matter of both bioclimatic and urban-specific (i.e. soil sealing, functional zoning, settlement history) factors, resulting in a very high variability in space and time. Urbanization effect on the SOC stock's spatial variability was clearly shown in the developed maps of the regional SOC stocks' and variance coefficients. The highest variability was shown for the urban areas and inclusion of urban soils into the regional analysis almost doubled the estimated variance in SOC stocks. Similar findings were reported by soil carbon assessment in US (Pouyat et al., 2006), where high variability of urban SOC was shown. Excluding urban soils from regional carbon assessments will probably under-estimate spatial variability in an urbanized region.

Urbanization effect on temporal variability of SOC stocks was investigated in the thesis for different time scales. Considerable dynamic of the regional SOC stocks resulted from several decades of urbanization was clearly illustrated and positive net effect of urbanization on SOC stocks was projected by all three plausible urbanization scenarios. Short-term (diurnal and inter-seasonal) temporal variability of urban SOC stocks estimated through soil respiration and approximated by basal respiration was analyzed as a function of bioclimatic conditions (i.e. soil temperature, moisture, chemical features) and anthropogenic disturbances. However, expanding these patterns to the regional level was challenging due to the methodological constrains.

A novel methodology was developed to analyze spatial-temporal variability of SOC stocks in urban areas. Stratified random sampling allowed considering both long-distance variability between bioclimatic zones and short-distance variability within settlements. Adapting digital soil mapping technique to urban-specific factors increased modelling accuracy and highlighted the hotspots of SOC variability. Mapping basal respiration as a proxy of soil respiration gave an opportunity to guess on the potential soil carbon effluxes and their spatial patterns in the region.

My thesis clearly shows evidence of high SOC stocks stored in urban soils (especially in the subsoil layers) and urban soil respiration, surpassing one from adjacent cropland and forest soils. Urban soils were major carbon hotspots on the maps, illustrating spatial variability in SOC stocks and basal respiration in the Moscow Region. Therefore excluding urban soils from the regional' assessment of SOC stocks would indeed underestimate SOC stocks and their spatial variability. The implemented methodology and obtained outcomes refer to the Moscow Region but my approaches can be used in other urbanized regions worldwide. Although all the urban areas are specific, methodological constrains in spatial and temporal analysis of soil features and functions are very similar.

The consistent analysis of soil carbon concentrations, stocks and fluxes and their variability in space and time, conducted for different soil and land-use types in the highly urbanized Moscow Region clearly showed a positive net effect of urbanization on soil carbon stocks. This is the most important finding of my thesis. It questions a traditional view on urbanization as a soil threat and highlights a potential of urban areas to provide important soil functions and ecosystems services. High capacity of urban soils to store carbon and the dominant anthropogenic effect on urban SOC spatial-temporal variability must be considered in urban planning sustainable cities of the future.

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SUMMARY

Urbanization is an increasingly important trend and responsible for large environmental changes worldwide. In the beginning of 21^{st} century urban population overtook rural population and two-thirds of the worlds' population is projected to live in cities by 2050. Traditionally, urbanization studies focused on the negative environmental effects, including air and water pollution and soil degradation. However, recent studies highlight the potential of urban ecosystems to provide and support important functions and services, including carbon sequestration. Soils are the largest terrestrial carbon sink, but they also have the potential to emit carbon to the atmosphere through, for example, soil respiration. In comparison to natural and agricultural soils, urban soil organic carbon (SOC) stocks remain poorly understood. Although globally urban areas occupy less than 3%, regionally one tenth of the territory can be urbanized. Specific features and heterogeneity of urban soils hinder studying their role in regional carbon balance and urbanization effects on SOC stocks. This information is, however, necessary for land-use planning in such urbanized areas as Moscow Region. The Moscow Region is the most urbanized region in Russia with Moscow city as the capital. Urban areas in the region exceed one tenth and continue to expand since 1990s. The New Moscow project recently announced by Russian government will expand the legal borders of Moscow City 2.4 times, resulting in rapid urbanization on more than 2500 km^2. Possible consequences of urbanization on the regional SOC stocks are not studied yet. Therefore, this thesis aims to identify and quantify the effects of urbanization on spatial variability and temporal dynamics of SOC the stocks in the Moscow Region.

To achieve this research aim SOC stocks in the Moscow Region were analyzed, mapped and modelled. Conventional approaches to analyze spatial variability and temporal dynamics of SOC stocks were reviewed and adapted for the specific features of urban soils, including i) an influence of a combination of natural (e.g. climate and vegetation) and urban (e.g. soil sealing, functional zoning) factors, ii) high short-distance variability, iii) contribution of subsoil layers to SOC stocks. Urban and non-urban (i.e. forest, meadow and cropland) soils in the Moscow Region were sampled with a stratified random sampling design. Sampling points were chosen inside and around the settlements of different age and size, as well as located in different bioclimatic zones. Recreational (e.g. parks and green zones), residential (e.g. yards and public courts) and industrial (e.g. highway sides and gas stations) were observed inside the settlements. In addition to a traditional composite topsoil (0-10cm) sample, an aggregated

subsoil (0-150cm) sample was analyzed. This provided information on the subsoil contribution to SOC stocks, which is rare for studies into urban soils (Chapter 2).

Comparative analysis of urban and non-urban SOC contents in the Moscow region provided three important outcomes: i) urban soils contained in average 2.37% SOC (SD = 1.93%), which was significantly ($t<0.05$) higher than 2.74% (SD =1.6%) in non-urban soils; ii) subsoil contribution to total SOC in urban soils was substantial and iii) spatial variability of SOC in urban soils was very high (Chapter 3). Spatial variability of SOC stocks in the Moscow Region was further analyzed trough digital soil mapping (DSM), relating obtained field data to auxiliary driving factors, including conventional and urban-specific factors. Three alternative general linear models were implemented: i) excluding urban areas from the analysis (non-urban model); ii) including urban areas but only considering traditional soil forming factors (conventional model); iii) including urban factors (urban-specific model). The best performance was shown for the urban-specific model, whereas the conventional model dramatically overestimated carbons stocks and underestimated SOC variability. The urban-specific model indicated a total SOC stock of 858 Tg and a specific SOC stock of 18.8% Gg/km^2 (SD=11.8 Gg/km^2) for the Moscow Region. Urban areas showed the highest spatial variability and specific carbon stocks, 90% of which was stored in subsoils (Chapter 4).

The spatial heterogeneity of urban SOC stocks is further complicated by their variability in time. Analysis of soil respiration (Rs) as the main soil carbon efflux enables understanding SOC temporal dynamics. Urban Rs is sensitive to climatic factors and anthropogenic disturbances. Both direct and indirect measurements were implemented to measure spatial-temporal variability of Rs at the key plot in Moscow city. Direct approach included intensive field measurements in forest, cropland and urban sites of the key plot by infrared gas analyzer (June-October 2013, 50 points, 9 time repetitions per point). At the same sites Rs was also measured indirectly through basal respiration (BR) analyzed in standardized conditions (32 points, 1 repetition per point). High Rs spatial variability was obtain for the key plot with the highest 42.9 g CO_2 m^{-2}day^{-1} obtained for urban green lawns, which was four times higher than in cropland and two times higher than in forest site. Indirect BR measurement gave to the opposite the highest respiration for the undisturbed forest sites. Different spatial patterns given by direct and indirect Rs measurements are explained by different process they reflect. Direct Rs refers to an instantaneous carbon efflux, influenced by soil temperature, moisture and anthropogenic disturbance, whereas BR is likely a potential microbial carbon efflux, driven by soil features, like SOC content and pH (Chapter 5). Although Rs and BR gave different spatial distribution, spatial variability estimated through variance coefficients was similar for both approaches, presenting BR as a relevant proxy to analyze regional variability of soil respiration. This outcome allowed to expand research area to the Moscow Region through implementing DSM approach to BR measured at the same locations as SOC in Chapter 3. Resulted model explained more than 50% of total BR variance (R^2 = 0.51) and confirmed the previous findings on the remarkable contribution of urban areas to SOC stocks' spatial-temporal variability in the region (Chapter 6).

Finally, obtained outcomes on urban SOC stocks, their spatial and temporal variability in comparison to non-urban areas were used to model urbanization effects on SOC stocks in the Moscow Region. The net urbanization effect on SOC stocks includes negative influences of construction and soil sealing and positive effects of green areas establishment and may differ for soil types and bioclimatic zones. I explored possible net effects of future urbanization on soil SOC stocks in the Moscow Region. Urbanization was modelled as a function of environmental, socio-economic and neighborhood factors. This yielded three alternative scenarios: i) including neighborhood factors; ii) excluding neighborhood factors and focusing on environmental drivers; and iii) considering the New Moscow Project, establishing 1500km^2 of new urbanized area following governmental regulation. All three scenarios showed remarkable urbanization on 500 to 2000km^2 former forests and arable lands. A positive net effect was shown by all the scenarios with 5 to 11 extra TgC. The highest increase was reported for less fertile Orthic Podzols and Eutric Podzoluvisols, whereas the effect was not significant in Orthic Luvisols, and Luvic Chernozems. The highest increase of both topsoil and subsoil C stocks occurred in the New Moscow scenario with the highest urbanization (Chapter 7).

In conclusion, my study clearly shows multiple and versatile effects of urbanization on SOC stocks. It was proven that urban soils can contain considerable amount of carbon, which is comparable or surpassing carbon stocks in natural soils. Development of the novel methodology enabled analyzing spatial-temporal variability of urban SOC stocks and highlighted the important role urban soils play in regional carbon balance. Finally, the consistent analysis of soil carbon contents, stocks and fluxes and their variability in space and time, conducted for different soil and land-usy types in the highly urbanized Moscow Region clearly showed a positive net effect of urbanization on soil carbon stocks. This is the most important finding of my thesis and questions a traditional view on urbanization as a soil threat and highlights a potential of urban areas to provide important soil functions and ecosystems services. The potentially high capacity of urban soils to store carbon and the dominant anthropogenic effect on urban SOC spatial-temporal variability should be considered in urban planning sustainable cities of the future.

ACKNOWLEDGEMENTS

To Grigorii Rozenberg, my grandfather

My grandfather passed away November 12th 2015 – six days before my thesis was finally approved. I saw him in August for the last time in Aachen, where he lived and I stayed on my way home from Wageningen. I had just submitted the thesis and we were discussing how nice it would be to celebrate the thesis defence with all our family. My grandfather was not a scientist. He was a building constructor. During his 79 years life he worked all over Soviet Union from polar deserts to volcanic valleys of Kamchatka. In the late 1970-s Moscow city was getting ready for the Olympic Games and workers from all Soviet republics were sent to the capital to contribute to the Olympic construction. My grandfather was directing the group from Moldova and many living houses and sport infrastructure he constructed are still in use. He and my grandmother moved to Germany in the late 1990-s and Aachen was the first place abroad which I visited as an Erasmus exchange student in 2008. Since then I felt support, love and care of my grandparents every day during almost seven years that it took me to complete my PhD project. Several weekends per month I travelled to Aachen and returned with an amazing red bag, full of tasty and healthy food, my grandparents prepared for me, so I "didn't have to lose time for cooking and could concentrate on my work". For these years I imported to Netherlands such amount of meat, sour cream and vegetables, that, probably, are questioned by customs. But I'm pretty sure that without this red bag my PhD thesis would not be possible, because when you feel such a support, you can never disappoint the people who believe in you. Sadly, my grandfather will not join the defense and share this happiness with all of us. I would like to devote this thesis to his memory. Sadly, I can't do more for him…

A PhD project is a long journey. Maybe it is even closer to a long run, where you have strict time limits to keep, check points to pass and requirements to conform to stay in the race. My PhD run started in 2008, when I got involved in the first round of the IAMONET project, supporting students mobility between Russia and the EU. I acknowledge the project and I'm personally very thankful to Ewa Wietsma, the project coordinator at Wageningen University. You not only helped to solve very practical and important issues during the first months of my Wageningen life, like accommodation, health insurance and opening a bank account. You also guided me through all these years and your support, for example, at the presentations I gave for the research groups, was very important for me.

Professional runners have coaches, whereas PhD students are trained and guided by the supervisors. I had two, that is a rather ‘modest’ number for Wageningen, but seemed a real ‘luxury’ for me, since in Russia we always only have one. Rik Leemans was my promoter. I can imagine that supervising me was not easy, especially during the first year, when the differences in background, mentality and general attitude to what it is to be a PhD student in Russia and in the Netherlands, resulted in some misunderstandings. However, being supervised by you was also not a piece of cake, to speak frankly. During first 15 months I wrote 17 versions of the research proposals and none of them was approved. Sometimes I got really irritated and then my desire to prove that I can be a successful PhD candidate, was motivating me to continue working hard. Now, looking back to that period, I am very thankful to you, Rik, and for the experience you gave me. In the end, I got rather well trained and most of my further proposals got approved since then. Including the most important proposal in my life to my charming future wife Inna. You were always helpful when it was necessary and as long as it was necessary. No more, no less. May be, this the main feature of a professional supervisor and far-seeing manager. And of course, your editing is something to get an aesthetic pleasure from (as my Dad, also an experienced supervisor, says). From now on and for all my life I know that English is a verb language, whereas Russia is a noun language, as well as, that making ‘sloppy’ mistakes can disappoint a reviewer even if the content is good.

My daily supervisor, Jetse Stoorvogel, showed up in 2009, when the IAOMONET funding was almost over and future perspectives were very foggy. “We don’t have enough data? Let’s get the data!”- he said and arrived in summer 2010 to the ‘burning’ Moscow Region, where Dutch tourists were officially not recommended to go. Our sampling campaign that summer for me was the turning point of the PhD project. Not only because we got the lacking data, but because I understood that everything is doable when there is a clear aim. There are many things to acknowledge Jetse for: four field trips to Russia, joined papers, conference presentations and research proposals, wise practical pieces of advice and informal talks. During these years you became not only a supervisor but a friend for me and my family.

Although Rik and Jetse were responsible for different parts of my project’s supervision and each had his own view on the supervision strategy, we managed to work as a good team, especially when time scarcity required for maximal concentration. The WUR sandwich PhD fellowship, the paper in Landscape and Urban Planning Journal and finally the PhD thesis were definitely the results of our collaborative work. Another example of this collaboration was the shared funding I was getting from both Environmental System Analysis (ESA) and Soil Geography and Landscape (SGL) groups for the three months, before my sandwich PhD fellowship was approved. Talking about my supervisors, I would also like to thank Lijbert Brussaard for being honest and straight to give up supervising me, enough far-seeing to recommend me to the SGL group.

Runners rarely run alone. A PhD race is also a group run. During my PhD project I was happy to be a part of two groups. Since my PhD run was a long one, I got to know several 'generations' of ESA PhD students. I started together with Serge, Morgan, Thu, Hongjuan and Claudia, and we had a lot of fun together. The farewell dinner of Hongjuan in Serge's place is a good example. Chun cooked her usual dozen of 'very simple' delicious snacks and the conversation was so nice that we ran out of all Serge's alcohol stocks, collected for many years. Sometimes, when I recognize that I witnessed the first days of the PhD projects of Alexander and Katalin, who are now the 'modern classics in ecosystems services', or the period, when Matthias and Roy were referred as YESA (young ESA), I really feel that it is not polite to stay in so long. Working in ESA gave me a lot in getting a mature scientist. Working with Dolf, Carolien, Ria, Karen, Nynke, André, Lars, José, Wim, Mathilde, Maryna, Halima, Yafei and many other members of ESA staff was a great pleasure. Some of the ESA fellows became my close friends, like Sander, Alexander and Katalin. Relations with some others were more professional. Anyway, staying in ESA was indeed a very pleasant period of my personal and professional life. Unfortunately, I was not that much involved in the social life of SGL group, where I spent the last three years. Working on the thesis, papers and research proposal required too much time, which I had to borrow from social events. However, meetings, for example, at the dinners in Jetse's house or a barbeque near Forum brought many nice people, like Jakob, Gerard, Cathelijne, Mieke, Simona, Rafael, Chantal and Maricke, to my life. It was a great pleasure to work with the group. I promise that when (if) I come back in February as an Erasmus PostDoc I will be more sociable, will not miss coffee breaks and especially Friday cakes.

Although I started in Wageningen in 2009 and hope to complete in 2015, a six year period, most of this time I spent in Russia. These years included many exciting and important events, including establishing a new laboratory of agroecological monitoring in Russian State Agrarian University (RSAU) and teaching initially as a senior lecturer and then as an assistant professor in Peoples' Friendship University of Russia (PFUR). My colleagues from RSAU and PFUR were always supportive and ready to help, when usual visits to

Wageningen constrained following teaching and research schedule. Lecturing and supervising students in PFUR gave me additional energy, inspiration and even joy to supervise and to be supervised at the same time.
Race runners derive strength from the fan’s support, whereas PhD students are mainly supported by their families. For me, my family – parents, wife, brother, grandparents, parents in law, aunt and uncle – were the main motivators, an energy source and a ‘calm haven’ to have rest for new struggles. Four of my family members (my parents, my wife and my mother in law) are soil scientists by background. Thus I could gain not only general support, but also professional help which is rare and valuable. A new family member showed up two years ago as a prize, runners are sometimes given at the end of the race. My prizes’ name is Veronica. She is my adorable daughter and the most loved human being.
My PhD project turned to be a long race, probably, more similar to a marathon. December 8th 2015 is scheduled to cross the finishing line. Several pages are not enough to recollect all the nice memories. My Kurdish friend Yusuf, football and boxing team members and coaches, corridor mates and Erasmus exchange students and colleagues from USA, Brazil, France, Italy, Russia…Wageningen is not only a wonderful place to study, it is also the center for international communication. Looking back, I think that the most valuable for me will be even not the doctoral status, obtained in Wageningen, but all the wonderful people, I met on the way, mentioned or not mentioned in these acknowledgments. Thanks to you all. We finished the marathon and it is our common victory. This race is over, but there are many other races to go. I hope, we can make them together.

ABOUT THE AUTHOR

Viacheslav (Slava) Vasenev was born in Kishinev, Moldavian SSR on May 20th 1986. When he was one month old, his parents took him to Moscow, where they were doing PhD projects in Moscow State University. Since then, Slava remained passionate to travel and higher education. Slava entered Moscow State University in 2003 as a first year student after living in Kursk city in the south-west of Russia for 14 years. Being a ‘hereditary’ soil scientist, he chose the Soil Science faculty and never regretted this decision afterwards.

As a student, Slava was always interested in the role soil plays for humans and the environment, soil functions’ analysis and soil quality assessment. His course work was based on the results from exciting expeditions to the historical Kulikovo Field (Tula region) and the Central forest preserve (Tver region), obtained excellent marks and was allowed to present at students’ conferences. Slava obtained a diploma of additional education in landscape design and got involved in urban greenery. This aroused his interest to urban ecosystems. Slava’s diploma was focused on the ecological standardization of urban soils. In 2011 Slava defended his PhD project on assessing environmental functions of urban constructed soils and obtained his first doctoral degree in Soil Science.

In 2008 Slava arrived to Netherlands for the first time as a participant of IAMONET program and liked Wageningen so much that stayed there for six years, at first as an exchange student and then as a sandwich PhD student. In parallel to the PhD project, Slava was involved in teaching and research in Russia. By now he is an assistant professor in the Peoples’ Friendship University of Russia and a senior researcher in the Russian State Agrarian University. Environmental functions and services of urban ecosystems and particularly urban soils remained the main topic for Slava’s research projects, lectures and presentation. Slava is actively involved in international scientific and educational collaboration. During the past three years he participated in five international research projects and leaded two of them. He gave oral presentation on twenty conferences in Europe, America, East Asia and Africa. Slava is also very enthusiastic about the double-diploma master program “Management and design of urban green infrastructure”, which he set up in collaboration with Tuscia University (Italy).

In 2012 Slava happily married his course mate and soil scientist Inna. Now they raise their wonderful two-years old daughter Veronica. Slava would like to continue studying ecology of urban ecosystems and hopes to contribute to the development of sustainable cities of the future.

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The Netherlands Research School for the
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Wageningen, 8 December 2015

the Chairman of the SENSE board	the SENSE Director of Education
Prof. dr. Huub Rijnaarts	Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

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The SENSE Research School declares that **Mr Viacheslav Vasenev** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 67 EC, including the following activities:

SENSE PhD Courses

- Environmental Research in Context (2009)
- Research in Context Activity: 'Developing and teaching a Master course on Urban Ecology at Peoples Friendship University of Russia (PFUR)' (2014)

Other PhD and Advanced MSc Courses

- Geo-Information Tools, Wageningen University (2009)
- Advanced Statistics (2010)
- Summer school GISLERS-2010, Salzburg University (2010)
- Spatial Modelling and Statistics, Wageningen University (2010)
- Winter school CMSS 'Modelling climate change impacts on water and crops at different scales', Alghero, Italy (2012)
- Eddy covariance Training Workshops, Li-Cor Biosciences, Vienna, Austria (2013)

Management and Didactic Skills Training

- Lecturing at the Summer School Moscow International Ecological Research School MOSES (2012-2013)
- Teaching in the MSc courses 'Data analysis and statistics' and 'Urban ecology', Peoples' Friendship University of Russia (2014)
- Co-converner of the session 'Soil environmental functions and land quality evaluation for land-use optimization' at the General Assembly of the European Geoscience Union (EGU) (2015)
- Co-converner of the session 'Soil ecological functions and ecosystem services: from concepts to application' at the 7th Congress of the European Society for Soil Conservation (ESSC) (2015)

Oral Presentations

- *Driving factors behind spatial variability of carbon stocks and fluxes in urban soils of Central European Russia*. 20th World Congress of Soil Science, 7-14 June 2014, Jeju, South Korea
- *Land use influence on 3-D distribution of soil microbiological activity in forest-steppe zone of Central Russia*. European Geosciences Union (EGU-2014), 28 April-2 May 2014, Vienna, Austria
- *Comparative analysis of the spatial variability in urban soil organic carbon at regional and local scales*. IUSS Ulm Conference, 1-6 October 2013, Ulm, Germany
- *How considering urban soil can improve regional soil organic carbon assessment and mapping*. 7th International Conference of the Urban Soils Working Group (SUITMA7), 15-20 September 2013, Torun, Poland

SENSE Coordinator PhD Education

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