

Changes of soil organic carbon stocks and CO₂ emissions at the early stages of urban turf grasses' development

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Published online: 27 August 2016
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Abstract Urbanization coincides with remarkable expansion of turf grasses and their increasing role in environmental processes and functions, including carbon (C) sequestration. Soil organic carbon (SOC) stocks in turf grass soils are substantial, however, an intensive soil respiration is also likely. Therefore C sequestration in turf grasses remains uncertain, especially at the early stages after development, when C uptake and CO₂ emissions are unbalanced. We analyzed changes in SOC stocks and CO₂ emissions at the experimental turf grasses in Moscow megapolis during the three years period after establishment. An influence of the three contrast depths of organic layers (5, 10 and 20 cm) on soil and biomass C and on the ornamental functions of turf grasses was studied. Total CO₂ emission from the turf grasses during the observation period exceeded C uptake in grass and root biomass by two to three times. Therefore the turf grasses at the early stages of development are important source of biogenic C. Although the C losses were substantial, CO₂ emission decreased and C uptake in biomass increased by the end of the observation period. The highest ratio of sequestered and emitted C was obtained for the thick turf grass soil constructions with a 20 cm organic layer. The highest ornamental value, indicated by the projective cover and sprout density, was also obtained for the thick

turf grasses, which is essential to consider for developing the best management practices and sustainable turf grass soil constructions.

Keywords Urban soil constructions · Green lawns · Soil respiration · C balance · Ornamental functions · Moscow

Introduction

The environmental consequences of urbanization have recently become increasingly important (FAO 2013). Urbanization coincides with substantial alterations in vegetation and soils (Pickett et al. 2011). Urban soils are dominated by the anthropogenic influence, resulting in specific features and processes, including sealing, pollution and over compaction (Stroganova et al. 1997; Lorenz and Lal 2009). As a result urban soils are diverse in types and morphological features, varying from slightly disturbed semi-natural soils to completely artificial soil constructions (Rossiter 2007; Prokofyeva et al. 2011). Historically, the quality of urban soils was assessed based on their agrochemical features and pollutants' concentrations (Zhideeva et al. 2002; Gerasimova et al. 2003). However, recent studies have focused on functions and services provided by urban soils (Raciti et al. 2008; Vasenev et al. 2012; Morel et al. 2014).

Carbon (C) sequestration is an important soil function, supporting such ecosystem services as soil fertility maintenance and climate mitigation (MA 2003; Lal 2004; Blum 2005). In comparison to natural areas and croplands, information on C stocks in urban soils is scarce. Some studies report high soil organic carbon (SOC) stocks in urban soils (Pouyat et al. 2006; Raciti et al. 2011; Vasenev et al. 2013), however, C-sequestration in urban soils remains debatable (Vasenev et al. 2015). High urban SOC stocks are often explained by

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increased net primary productivity of urban vegetation (Jo and McPherson 1995; Gregg et al. 2003; Nowak et al. 2006). However, it is argued that the urban SOC is mainly brought in with added organic composts and turf-sand mixtures (Prokhorov and Karev 2012; Beesley 2012; Vasenev et al. 2014a). The problem that emerges is that the substantial CO₂ emissions reported for urban soils question the sustainability of the SOC stocks (Koerner and Klopatek 2002; Kaye et al. 2005; Sarzhanov et al. 2015).

High spatial-temporal variability of urban soils increases uncertainty in estimates of urban SOC stocks and CO₂ emissions (Vasenev et al. 2014b). Conventional urban soil surveys, based on random sampling, likely yield a mixture of urban soils which are of different age, contain different organic and mineral horizons and are exposed to different managements. For example, the urban soil surveys carried out in the UK (Rawlins et al. 2008), Shanghai (i.e.; Naizheng et al. 2012) and Florida (Ross et al. 2016) showed high variances in SOC stocks, but the biochemical processes (i.e. C sequestration and CO₂ emission) were not studied due to high heterogeneity of the urban soils. This heterogeneity constrains the revealing role of urban soils as a net C source or sink (Grimmond et al. 2002; Pataki et al. 2006). Studying a specific urban soil sub-type reduces the heterogeneity and enables focusing on the processes influencing SOC stocks.

Turf grass soils are artificial urban soil constructions under green lawns (Jo and McPherson 1995; Bandaranayake et al. 2003). In soil classifications ‘urban constructed soils, (Constructozems)’ (Prokofyeva et al. 2011) and ‘Garbic Technosols’ (WRB 2014) are the corresponding definitions of the turf grass soils. The main morphological features of the turf grass soils are an artificial organic horizon (e.g. including peat, peat-sand mixtures, composts or organic waste materials) with a clear boundary to the underlying mineral technogenic horizons (e.g. including sand, loam, gravel or drainage) within 100 cm from the surface (Prokofyeva et al. 2014). Turf grasses can occupy a substantial part of non-sealed urban surfaces (Robbins and Birkenholtz 2003), therefore their contribution to regional C balance is essential and a prompt analysis of SOC stocks and CO₂ emissions in turf grass soils is necessary (Pouyat et al. 2009; Selhorst and Lal 2011).

High temporal variability is typical for SOC stocks and CO₂ emissions in turf grass soils. Temporal dynamics in CO₂ is mainly influenced by seasonal and inter-seasonal deviations in soil temperature and moisture (Bremer and Ham 2005; Delden van et al. 2016). Changes in SOC stocks become evident over long time periods when turf grass soils of increasing age (time passed from the establishment) are compared. For example, turf grass systems studied in USA were shown to sequester around 1.0 MgC ha⁻¹ yr.⁻¹ (Qian and Follett 2002). A remarkable increase of C stocks was modelled for turf grasses after 10–50 years of clipping (Qian et al. 2003; Zircle et al. 2011). Analysis of the carbon footprint

in contrast showed that the C sink capacity of turf grasses can be offset during the first decades by C emission, depending on the land-use and management practices (Selhorst and Lal 2011; Kong et al. 2014). Studying temporal changes of SOC stocks and CO₂ emissions in turf grasses is critical to predict their role in C sequestration. So far, the ‘age’ factor in C assessments of turf grasses was addressed either by dynamic models (i.e. CENTURY) or by implementing the chronosequence approach (Qian et al. 2003; Bandaranayake et al. 2003; Selhorst and Lal 2013). Both approaches are relevant to analyze for analysis of long-term dynamics, however, the rapid changes in SOC stocks and CO₂ emissions at the very early periods of turf grasses’ establishment lack attention.

This research aimed to fill this knowledge gap and analyzed changes in SOC stocks and CO₂ emissions in newly established turf grass soils. The investigated sites locate in highly urbanized Moscow megapolis, where turf grass is a substantial part of urban green infrastructure. Two scientific hypotheses were tested: i) an intensive mineralization of organic substrates would result in high CO₂ emissions and rapid depletion of SOC stocks in turf grass soils at the early stages of development; ii) the proportion between C emission and uptake in the turf grasses would depend on the depth of organic horizon. To test the hypothesis the experimental model turf grass soils (the fixed sequence of soil layers, simultaneous establishment) with different depths of the organic horizon were observed during the first three years after establishment.

Materials and methods

Research area

Moscow city is located in the southern mixed forests vegetation subzone of the taiga-forest zone. Zonal Eutric Podzoluvisols on the moraine loam 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. However, these numbers have clearly decreased over the last few decades. The average annual precipitation is close to 650 mm. The precipitation / evaporation ratio is 1.3–1.4. Summer period lasts from mid-May to the beginning of September. The winter period lasts 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 2009).

Moscow city is the main economic and tourist centre of Russia. Recently urban greenery and sustainability of the

urban green infrastructure, including turf grasses is gaining increasing attention and is among the main concerns of the municipal government. Moscow climatic conditions, with high temperatures in summer and a precipitation surplus in spring and autumn, are favorable for intense mineralization of organic substrates used for turf grass' establishment. In the locations, exposed to high anthropogenic pressure (i.e. highway buffer zones and areas with high recreational load), the losses of soil C become substantial. To avoid urban lawns' degradation, the losses in soil C are compensated by regular addition of new organic substances. These renovations increase costs of lawn maintenance and may have negative environmental consequences for CO₂ emission, which has become an important concern for the Moscow city municipality. Although the physic-chemical features of turf grass soils are controlled by sanitary regulations and greenery guidelines (e.g. GR-514 2011), the depth of the organic horizon varies, depending on the land-use and management (i.e. golf courses, football fields and ornamental lawns) (Belobrov and Zamotaev 2007). Data on changes in SOC stocks and CO₂ emissions from young (newly established or renovated) turf grass soils with different constructions are necessary to develop sustainable management practices for turf grass soils in Moscow.

Site description

The investigated turf grasses were constructed at the flat rectangular plot (20 m by 100 m) located at the Russian State Agrarian University field experimental station of in northern part of Moscow city (55°50'N; 37°33'E). Eutric Podzoluvisols is the predominant soil type at the research area, however, at the experimental site, there are some evidences of agrogenic transformation (Mazirov and Safonov 2010). Prior to research the experimental plot was dominated by plant species, typical for abandoned urban lawns: *Poa pratensis* L., *Dactylis glomerata*, *Rumex confertus* and *Taraxacum officinale*. The experimental site adjoins the university golf course in the south-east, a highway and railway in the west and north-west, and experimental croplands on the remaining sides (Fig. 1a). The model turf grasses were constructed at the experimental site in September 2012. Special transparent containers were designed with perforated neutral plastic walls and bottom with an experimental surface 0.5 m², total height – 0.5 m (patent RU 150235 U1). The turf grass soils were inserted in these containers. The physic-chemical features of organic substrates and the layer sequences of were in coherence with the municipal regulations (GR-514 2011) and represented typical turf grass soils for Moscow. The profile of the model turf grass soils included the following sequence of layers from the bottom to the top: i) 20 cm of natural underlying soil horizon and ii) 30 cm of artificial soil layers (Fig. 1b). The natural underlying soil horizon consisted of the mineral horizon (illuvial B₁)

of the Eutric Podzoluvisol, which was excavated at the experimental site. The artificial soil layers included a mineral layer (bank sand) covered by an organic layer of turf-sand mixture, containing 30 % of sand and 70 % of valley peat by weight percentage, according to the design recommended for urban greenery in Moscow (GR-743 2015). The experiment was designed to have three turf grass soil constructions differentiated by the depths of the organic turf-sand layers of 5, 10 and 20 cm (hereinafter referred as 5TS, 10TS and 20TS respectively). The artificial soil layer was fixed to a depth of 30 cm (GR-743 2015, Vasenev et al. 2014a) with the corresponding mineral layers fixed to depths of 25, 20 and 10 cm (Fig. 1c). total seven experimental containers (three replicas for 10TS and two replicas for 5TS and 20TS) were installed on the soil at the ground level and were sown with classical lawn grass mixture (*Lolium perenne* – 45 %, *Poa pratensis* – 5 % and *Festuca rubra* – 50 %; following the recommendations of (GR-743 2015) for urban lawns , . (Fig. 1d). All the measurements started in summer 2013.

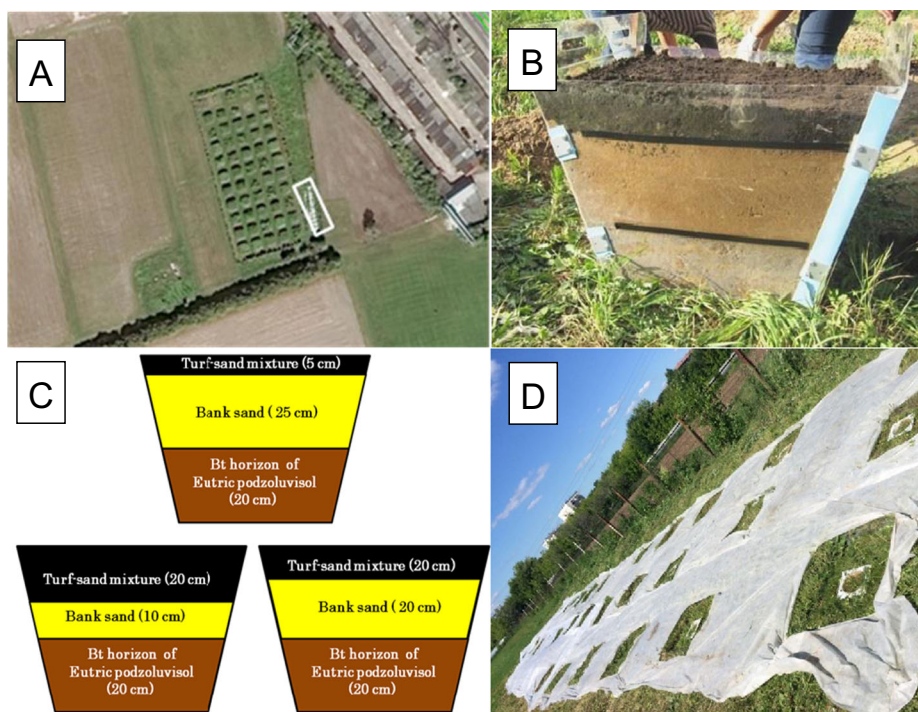
Experimental design

Changes in SOC stocks and CO₂ emissions in the model turf grasses were monitored since June 2013 (8 months after establishment) till November 2015 (38 months after establishment). Minimal management was applied to the turf grasses during the observation period to simulate the typical conditions for unmanaged urban green lawns, which dominate in Moscow. The studied turf grasses were neither artificially irrigated, nor fertilized. Lawns were cut monthly during the growing season (June–September). Changes in C stocks (soil and biomass carbon) and CO₂ emission (in situ soil respiration (Rs)) were observed during the growing seasons in 2013–2015. The SOC stocks were estimated for the periods of one, two and three years after turf grass's establishment were compared to analyze temporal changes. The amounts of C stored in biomass and C lost through CO₂ emission were quantified for each construction on the annual basis to estimate changes in C uptake/outflow ratios of the turf grasses over time. Since urban lawns are highly valued for their ornamental and aesthetic function, an integral lawn quality was assessed for all the investigated turf grasses in this study.

Soil CO₂ emissions

Soil CO₂ emission was estimated based on direct Rs measurements. Rs was measured in situ in three replicas per each turf grass using the chamber approach with an infrared gas analyzer Li-820 (Li-Cor, USA). Together with the Rs measurement the topsoil (0–10 cm) temperature (Checktemp thermometer, Hanna, Germany) and moisture (SM-300 probe, Delta-T, UK) were measured. Measurements were done seasonally through 2013 to 2015. A diurnal dynamics was

Fig. 1 The Experimental set-up: a research area **a**, an experimental container with turf grass soil construction **b**, a scheme of the investigated soil constructions **c** and an overview of the experimental plot after mounting the containers into soil **d**



measured to understand the Rs daily fluctuations and to determine the relevant time period for further measurements. Diurnal Rs dynamics were analyzed based on 24-h measurements with three hour intervals, carried out on the 10TS turf grass – in the middle of the growing season, the third week of July 2013. Subsequently, measurements were taken monthly from March to October, whereas Rs in winter periods (November–February) was considered negligible. The Rs results were used to estimate CO₂ emissions for each measuring period.

Soil C stocks

In each of the seven turf grass constructions composite soil samples ($n = 3$) were collected at a depth of 0–30 cm by augering (Edelman auger for loamy sand, D = 7 cm, Eijkelkamp, Netherlands) twice during each season; once in June and once in October. Soil samples were separated into mineral (sand) and organic (turf-sand) layers. Additional samples were taken from the turf-sand mixture and bank sand materials used for the turf grass' construction prior the establishment of the experiment (the null time). All samples were air-dried and roots' and plants' fragments were removed. Subsequently, the samples were sieved (1 mm) and pulverized using an agathic mortar. SOC concentrations were measured separately for each layer by the dichromate approach with the spectrophotometric end point detection (Vorobyova 1998). To avoid destruction of the turf grasses, only at the first and last sampling campaigns separate samples were taken to measure bulk density. Bulk density was measured separately for

mineral and organic layers using the core method (Shein 2007). Carbon stocks were estimated using Eq. 1. The amount of stones was negligible and therefore was not considered

$$\text{SOC}_{\text{st}} = \text{SOC}_{\text{con}} \times H \times \text{BD}/10 \quad (1)$$

Where SOC_{st} – soil organic carbon stock (kg C m^{-2}), SOC_{con} – soil organic carbon concentration (%); H – depth of the layer (cm) and BD – bulk density (g cm^{-3}).

Lawn biomass

Aboveground (grass) biomass was collected monthly during the growing seasons (June–September). The results for each month were summarized to estimate the seasonal aboveground biomass. Belowground (root) biomass was collected annually at the end of the season. Grass and root biomass were air dried and weighed. Carbon content in the collected biomass was estimated using the coefficient 0.45 (Makarenko et al. 2012). Grass samples collected in 2015 were air dried and pulverized. Contents of total sugar (monosaccharides and disaccharides) were measured in the grass samples using the Betrtan approach with picric acid to assess urban lawn' quality and stress resistance (Koshkin 2010).

Ornamental function of lawns

The projective cover (%) and sprout density (units m^{-2}) were analyzed monthly at each plot (following the Laptev's scale and recommendations of the National Turfgrass Evaluation

Program) (Kevin 2013; Shchepeleva 2015) prior to biomass cutting to assess the ornamental value of the lawns in this study.

Data processing and statistical analysis

C concentrations in soil and biomass were measured in three replicas and presented as mean \pm standard deviation. CO₂ emissions were estimated from the linear increase of gas concentrations per unit time, corrected for air temperature, atmospheric pressure and chamber volume-to-area ratio. The normality of the investigated parameters was checked by Shapiro-Wilk's *W* test. The homogeneity of variances was checked by Levene's test. The relationships between CO₂ emissions, soil temperature and moisture were examined by multiple linear regression analysis. 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).

Results

Climatic conditions

Inter-seasonal dynamics for the climatic conditions were observed at the experimental plot and were found to be typical for the temperate climate – a warm summer with average air temperatures between 18 and 20 °C and temperatures below zero in December–February. Rainfall events occurred between May and September, with maximal values and more than 70 % of annual precipitation occurring in September. Although the inter-seasonal dynamics were similar for all of the observed years, the differences between the years were substantial. The warmest summer followed by an autumn with the most abundant rains was observed in 2013 and the winter of 2014–2015 was the longest and the coldest. Based on the results for June–November periods, when the data for all three years was available, the year 2013 was the warmest and the wettest, whereas 2015 was the coldest and the driest. However, the year 2015 was warmer and drier than 2014, when January–November periods were taken into account (Fig. 2).

Soil CO₂ emission

Diurnal fluctuations, seasonal changes and inter-seasonal changes of the in situ R_s were analyzed at the investigated turf grasses to study the temporal dynamics in CO₂ emission. During the day R_s varied from the maximal 20 gCO₂ m⁻² day⁻¹ between 12 and 13 PM and minimal 15 gCO₂ m⁻² day⁻¹ at 4 AM (Fig. 3a). Maximal deviation from the average daily R_s was less than 20 %. Diurnal variation in R_s

was positively correlated with the soil temperature ($r = 0.63$; $p < 0.05$), however, soil moisture was an insignificant factor (Fig. 3b). R_s between 7 AM and 13 AM was similar to the daily average value, therefore this time period was considered relevant for further measuring R_s during the season.

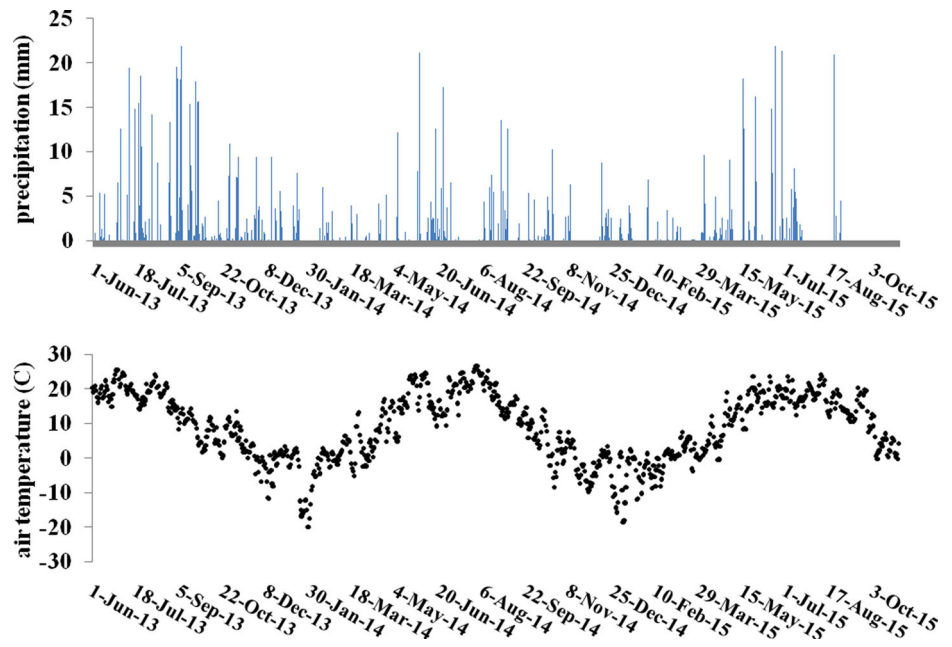
Substantial seasonal changes in R_s were obtained for the investigated turf grasses. The highest R_s was found in late spring to early summer (May–June) and the lowest R_s was obtained in October. Therefore, seasonal dynamics in R_s was in coherence with changes in air temperature. Positive correlation with soil temperature ($r = 0.71$, $p < 0.05$) and negative correlation with soil moisture ($r = -0.49$, $p < 0.05$) were found for R_s . Soil temperature and moisture together explained more than 50 % of the total R_s variance ($R^2 = 0.55$; $R^2_{adj} = 0.53$). Although the R_s seasonal dynamic was similar for all observed years, the average R_s differed between the seasons. R_s averaged for all turf grasses in 2015 was 25 and 30 % higher than in 2014 and 2013 respectively, however the difference was statistically insignificant. Different R_s values were also obtained for the turf grasses with different depths of organic layers. The highest R_s was shown for the 20TS exceeding 10TS and 5TS by 30 % and 20 % respectively. The difference between the constructions was significant during the summer period, when the largest seasonal fluxes were observed, whereas in March and October deviation between the constructions was negligible (Fig. 4).

The results of R_s temporal dynamics were used to estimate CO₂ emissions from the turf grasses during the observation period. The highest emission was estimated for summer period, which produced approximately 60 % of the annual emission. The total emissions summarized for the experimental period varied from 2.5 kg C m⁻² for the 10TS to 3.6 kg C m⁻² for the 20TS. When averaged for different depths, the total CO₂ emission was 8–11 % higher in 2015 than in 2014 and 40–60 % higher than in 2013 (however, in the latter only 5 months were considered). However, the total CO₂ emission for the summer months in 2013 was similar to 2014 and 40 % higher than in 2015 (Table 1).

Changes in SOC stocks

A substantial decrease of SOC concentrations was obtained for all turf grass soils during the study. The most rapid decline was found during the first year after the turf grass's establishment. The average SOC measured in October 2013 decreased 25–30 % compared to that in June 2013, whereas the total decline compared to the initial SOC concentration of turf-sand mixture was as much as 70 %. For the second and the third years there was an annual 10–15 % decrease in SOC concentrations]. In total, for the duration of the experiment, the average SOC concentration decreased almost two-fold; – from 7.5–7.8 % in June 2013 to 3.3–3.5 % in October 2015 (Fig. 5).

Fig. 2 Temporal dynamics in precipitation and air temperature at the experimental plot during the observation period in 2013–2015



Estimated changes in SOC stocks showed substantial differences among the turf grass soil constructions. SOC stocks were estimated for the organic and mineral layers separately

and then summarized. Bulk density of the organic layers measured in June 2013 was 1.0 ± 0.06 , 0.81 ± 0.15 and $0.70 \pm 0.17 \text{ g cm}^{-3}$ for 5TS, 10TS and 20TS respectively.

Fig. 3 Diurnal dynamics of soil respiration **a**, air temperature, soil temperature and moisture **b** at the experimental turf grass

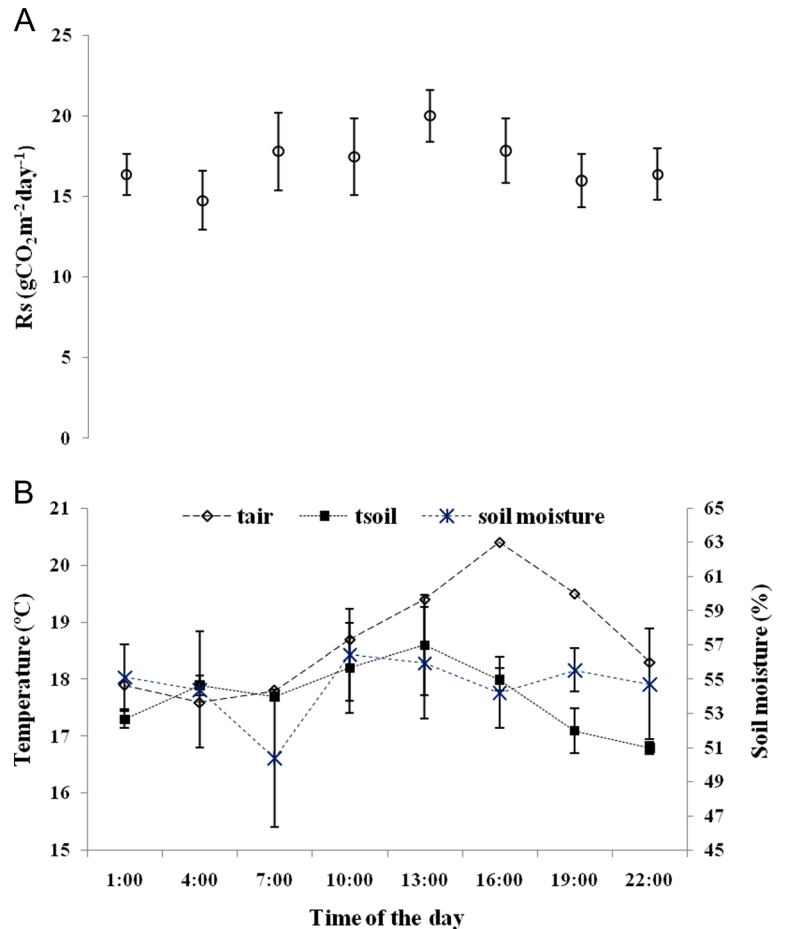
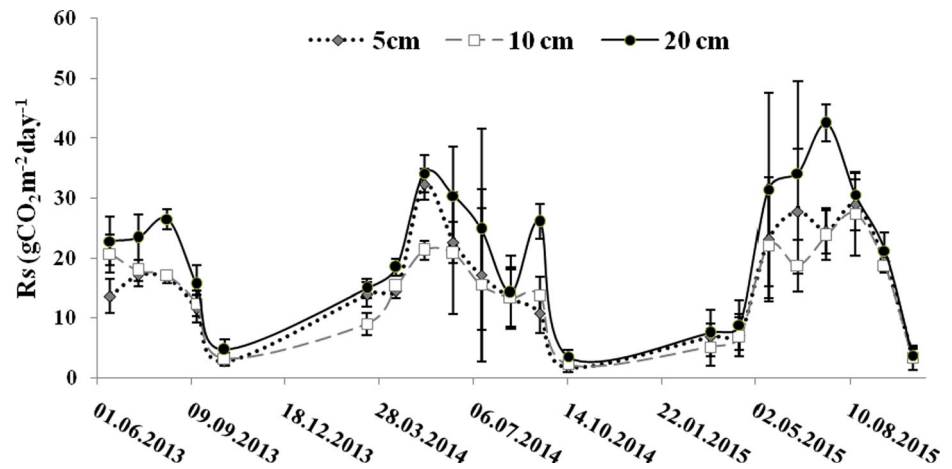


Fig. 4 Seasonal dynamic in soil respiration from the experimental turf grass soil constructions with the different depth of the organic layer



By October 2015 the bulk density of the organic layers increased 10–15 % on average, resulting in 1.15 ± 0.10 , 0.95 ± 0.12 and $0.81 \pm 0.11 \text{ g cm}^{-3}$ for 5TS, 10TS and 20TS respectively. Bulk density of the mineral layers was 1.3 ± 0.11 , 1.3 ± 0.10 and $1.0 \pm 0.10 \text{ g cm}^{-3}$ for 5TS, 10TS and 20TS respectively in 2013 and did not change significantly in 2015. The initial SOC concentrations in the mineral layers did not exceed 0.2 % in June 2013, whereas in 2015 they increased to 0.30 ± 0.02 , 0.41 ± 0.02 and $0.55 \pm 0.03 \%$ for the 5TS, 10TS and 20TS respectively. Total SOC stocks measured in turf grass soils in June 2013 were 4.1 ± 0.1 , 5.8 ± 0.2 and $11.0 \pm 0.4 \text{ kg m}^{-2}$ for 5TS, 10TS and 20TS respectively. The contribution of the mineral layer to total SOC stocks varied from 1 % in 20TS to 8 % in 5TS constructions (Fig. 6a). A substantial depletion in SOC stocks for the three years period was found turf grass soils. The largest 47 % depletion was obtained for the 20TS construction. SOC stocks in 5TS and 10TS in October 2014 were 75 % and 72 % from the corresponding stocks in June 2013. The contribution of mineral layers to total SOC stocks increased in 2015 with the maximal 34 % obtained for the 5TS (Fig. 6b).

Biomass C stocks

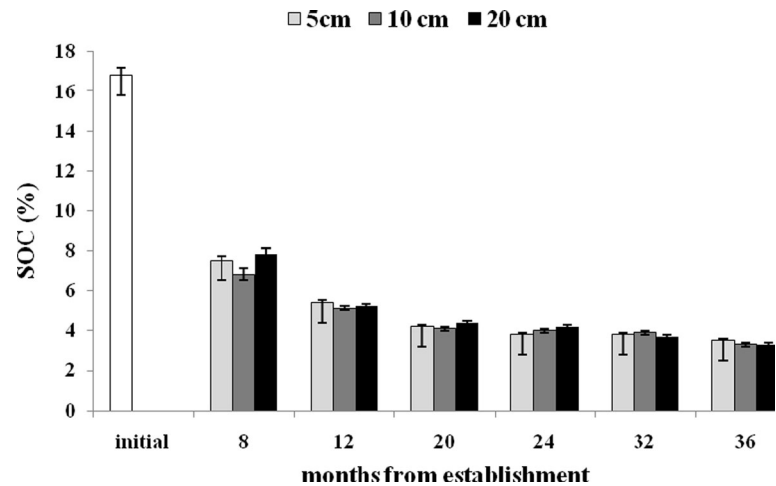
The lawn biomass increased from 2013 to 2015 following the development and maturation of turf grasses. The average aboveground and belowground biomass in 2015 were more than double compared to 2013. The obtained biomass was positively correlated with the depth of organic layer: the biomass at the 20TS constructions was 50 % and 100 % higher than for the 10TS and 5TS correspondingly. The contribution of roots to total biomass was 35–40 % in 2013 and slightly increased by the third year (Table 2).

The annual C uptake in biomass was compared to the CO_2 emission from soils to estimate C balance of the i turf grass systems. Carbon uptake did not compensate C emission for the turf grasses. The total C emission exceeded C uptake 5.3, 3.8 and 3.5 times for 5TS, 10TS and 20TS respectively, resulting in substantial C losses. The highest depletion of almost 2.6 kg C m^{-2} summarized for the three observation years was obtained for the 20TS. Losses for the 5TS and 10TS were 2.2 and 1.9 kg C m^{-2} respectively (Fig. 7).

Table 1 Carbon emissions (g C m^{-2}) from the experimental turf grasses with 5, 10 and 20 cm depths of the organic layer (5TS, 10TS and 20TS respectively), summarized for the whole observation period and for the summer periods (June–August) separately

Year	Number of observation months	5TS	10TS	20TS
Total for the year				
2013	5	504 ± 23	583 ± 34	761 ± 39
2014	8	1033 ± 33	911 ± 37	1362 ± 42
2015	8	1157 ± 38	1030 ± 35	1472 ± 52
Total	21	2694 ± 68	2524 ± 79	3595 ± 96
Total for the summer period				
2013	3	387 ± 15	455 ± 15	596 ± 26
2014	3	496 ± 16	373 ± 12	552 ± 17
2015	3	303 ± 44	278 ± 41	391 ± 66
Total	9	1186 ± 54	1107 ± 49	1538 ± 79

Fig. 5 Temporal changes in SOC concentrations in the experimental turf grass soil constructions with the different depths of the organic layer



Ornamental features and stress-resistance of turf grasses

The ornamental function of the investigated lawns was analyzed based on the projective cover and sprout density. Stress-resistance was determined by the ratio of mono- and disaccharides in grass biomass. Both projective cover and sprout density increased during the observation period. The average projective cover was already high in 2013 and changed only 2 % by 2015, giving in average 94 %. An increase in sprout density was more substantial and resulted in extra 1200 sprouts m^{-2} (23 % increase) in 2015 as compared to 2013. The sprout density for the 20TS turf grass was 20–40 % higher than for the other sites. The projective cover didn't differ between the sites significantly (Table 3). Monosaccharides contributed to 50–65 % of total sugars, indicating relatively low stress-resistance. The highest percentage of disaccharides was found for the 5TS turf grass, whereas in the 10TS turf grass it was the lowest (Fig. 8).

Discussion

C emission from turf grass soils at the early stages of development

Substantial CO_2 emission was obtained from the investigated turf grasses as a result of intensive Rs. The existing research of C balance in turf grass systems tends to focus on SOC stocks changes over time (Shi et al. 2006; Townsend-Small and Czimczik 2010) or in response to different management (i.e. clipping, irrigation or fertilization) (Qian et al. 2010; Lopez-Bellido et al. 2010; Zhang et al. 2013). Long-term in situ observations of Rs from turf grasses are few, therefore the possibility to validate the obtained results is limited. The Rs of 25–35 $g CO_2 m^{-2} day^{-1}$ from this study was similar to the average 35 $g CO_2 m^{-2} day^{-1}$ reported by Livesley et al. (2010) for turf grasses with minimal management in Victoria (Australia) and 30 $g CO_2 m^{-2} day^{-1}$ obtained by Ng et al. (2015) in Singapore (Singapore). However, the average Rs

Fig. 6 Carbon stocks in the organic and mineral layers of the experimental turf grass soils with 5, 10 and 20 cm depths of the organic layer (5TS, 10TS and 20TS respectively) at the beginning (June 2013) (A) and at the end (October 2015) of the experiment

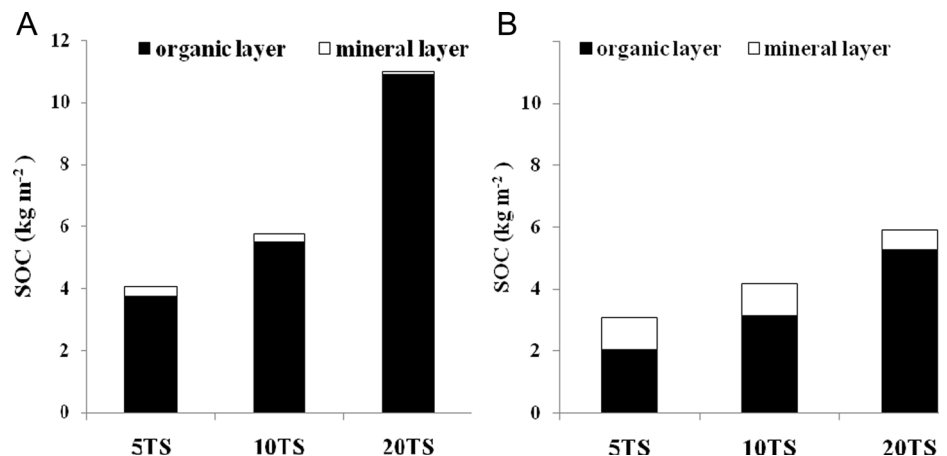


Table 2 Total biomass and biomass C stocks at the experimental turf grasses with 5, 10 and 20 cm depths of the organic layer (5TS, 10TS and 20TS respectively)

	5TS		10TS		20TS	
	Grass	Roots	Grass	Roots	Grass	Roots
Biomass (dry weight, g m ⁻²)						
2013	171 ± 2.3	89 ± 1.8	218 ± 2.5	114 ± 1.6	349 ± 3.1	207 ± 2.2
2014	355 ± 2.7	194 ± 2.8	458 ± 2.7	242 ± 1.3	714 ± 3.0	447 ± 3.0
2015	389 ± 2.0	220 ± 7.0	503 ± 4.0	286 ± 4.0	749 ± 3.0	495 ± 6.0
Biomass C stocks (g C m ⁻²)						
2013	77 ± 1.0	40 ± 0.8	98 ± 1.1	51 ± 0.7	157 ± 1.4	93 ± 1.0
2014	160 ± 1.2	87 ± 1.3	206 ± 1.2	109 ± 0.6	321 ± 1.4	201 ± 1.4
2015	175 ± 0.9	99 ± 3.2	226 ± 1.8	129 ± 1.8	337 ± 1.4	223 ± 2.7

values obtained in our study were higher than approximately 20 g CO₂ m⁻² day⁻¹ obtained by Fu et al. (2013) in Beijing (China) and by Weissert et al. (2016) in Auckland (New Zealand). Considering an artificial genesis of turf grass soils, a comparison to the broader range of urban soils is constrained by high variance of Rs results, obtained in different climates and for different functional zones. For example, Sarzhanov et al. (2015) showed an average Rs of 33 g CO₂ m⁻² day⁻¹ 27 g CO₂ m⁻² day⁻¹ in the industrial zone and the recreational area in Kursk (Russia) respectively. Jarvi et al. (2012) reported Rs of 26 g CO₂ m⁻² day⁻¹ at the university campus in Helsinki (Finland) and Decina et al. (2016) showed 17 g CO₂ m⁻² day⁻¹ emitted from soil at the recreational zone in Boston (USA). Although the diversity is high among the data reported on urban soil respiration, our findings are in good coherence with majority of the results available in the literature. The Rs measured for the turf grasses was almost one third higher than those reported for natural forested areas in similar bioclimatic conditions (Vasenev et al. 2015; Vizirskaya et al. 2015). This outcome corresponds to the other studies reporting higher Rs in urban soils, compared to natural and agricultural soils in Arizona and Baltimore (USA) (Koerner and Klopatek 2002; Kaye et al. 2005) and Shanghai and Nanjing in China (Sun et al. 2009; Zhang et al. 2010).

High temporal dynamic is often reported for urban soils' respiration as a result of seasonal fluctuation and different management regimes (Livesley et al. 2010; Li et al. 2011). Inter-seasonal Rs variability obtained for the observed turf grass soils was similar to those described for natural and anthropogenic soils in temperate climate with maximal respiration from May to July (Larionova et al. 2010; Kurganova et al. 2011; Vasenev et al. 2014a). A slight increase in Rs was shown between the observed years. The highest average Rs obtained for 2015 was likely caused by the increased root respiration, as it also substantially contributes to the total respiration as it was shown for the grassland soils (Hanson et al. 2000; Li et al. 2011; Sarzhanov et al. 2015). The CO₂ emission estimated for the summer period in 2015, however, was substantially lower compared to 2014, whereas the emission in 2013 was the highest among all the three observed years.

We observed specific artificial turf grass soils, where most of the factors, influencing CO₂ emission (i.e. physico-chemical features of organic and mineral substrates, depth and sequences of soil horizons, time of establishment and management) were controlled. This experimental design allowed focusing on the biochemical drivers of C emission from turf grasses. Since the observed turf grasses were exposed to minimal management, the emission was mainly driven by

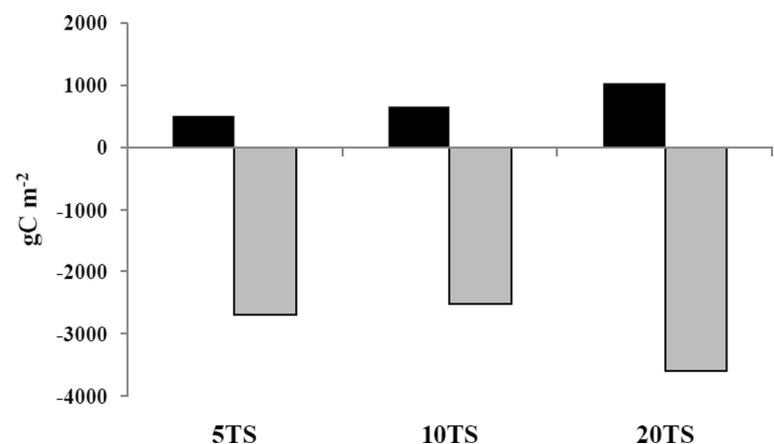
Fig. 7 Total C emission through soil respiration (grey boxes) and C uptake in biomass (black boxes) for the experimental turf grasses with 5, 10 and 20 cm depths of the soil organic layer (5TS, 10TS and 20TS respectively)

Table 3 The indicators of the ornamental functions, performed by the experimental turf grasses with 5, 10 and 20 cm depths of the organic layer (5TS, 10TS and 20TS respectively)

	5TS	10TS	20TS
Projective cover (%)			
2013	90	92	93
2014	93	90	95
2015	95	92	97
Sprout density (units m ⁻²)			
2013	4680	4500	5700
2014	4992	5123	6345
2015	5113	6210	7125

intensive mineralization of turf-sand mixtures in the organic layers of the soil constructions. These substrates are rich in labile forms of organic C which are easily mineralized by microorganisms (Lorenz and Lal 2009; Beesley 2012). This assumption is proved by a very intensive emission during the first year after establishment and substantial decrease by the third year, when a considerable amount of initial SOC stocks were already depleted. An intensive mineralization of SOC during the first year after the turf grass' establishment is confirmed by substantial decrease in SOC concentration and SOC stocks obtained between 2013 and 2015. Only 50–70 % of SOC stored in turf grass soils over an eight month period after establishment remained after three years, resulting in 2–5 kg C lost per each square meter. Therefore, the first hypothesis of the research was confirmed. The velocity of SOC losses were gradually decreasing with the time passed, which is likely an evidence of both depletion of initial stocks and stabilization of the turf grass system, when C emission to the atmosphere is partly compensated by C uptake through photosynthesis and humification.

C balance for different turf grass soil constructions

Total amount of C lost through intensive CO₂ emission during the first three years after establishment of the turf grasses was

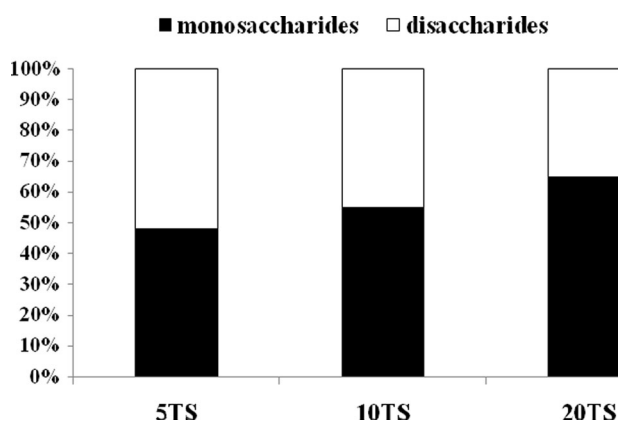


Fig. 8 Contribution of mono- and disaccharides to total sugars of the biomass at the experimental turf grasses with 5, 10 and 20 cm depths of the soil organic layer (5TS, 10TS and 20TS respectively)

not fully compensated by C uptake for all the studied soil constructions. The highest C depletion was obtained for the 5TS. Although CO₂ emissions from 20TS and 10TS turf grasses were substantially higher, the biomass production was substantial as well, whereas 5 cm depth of organic layers was apparently too shallow to support an intensive growth of the urban lawns. The 20TS turf grasses were the most balanced in terms of lost and sequestered C, however total depletion of the average 3.5 kg C m⁻² was obtained for 20TS during the observation period. This outcome clearly shows that the turf grasses at the early stages of development are important sources of biogenic carbon. Our findings confirm previous studies reporting an intensive C-mineralization in turf grass soils (e.g. Yao et al. 2009) and contradict the other research reporting C-sequestrations in turf grasses (e.g. Townsend-Small and Czimczik 2010). This contradiction, is likely due to different measurement periods. C-sequestration has been reported for decades, whereas we focused on the first three years after the establishment of the turf grasses.

Although, a negative C balance was found for the turf grasses during the whole observation period, the difference between C emission and C uptake decreased from 2013 to 2015 with 52, 76 and 86 % of C emissions compensated by C uptake for 5TS, 10TS and 20TS respectively. Moreover, for the summer period (when major biomass growth occurs), the negative balance in 2013 changed to positive already in 2014 with total C uptake more than double of C loss for 20TS in 2015. This finding is in good coherence with the results obtained by Qian et al. (2010), who used the isotopic technique to show a considerable contribution of root biomass to C-sequestration in four-years old turf grasses based on. In our study, the roots' contribution to total biomass also increased significantly by the third year. This is an additional evidence of turf grass' stabilization, since the humification processes and the corresponding increase of soil C stocks are likely driven by roots (Hanson et al. 2000; Kuzyakov and Larionova 2005).

The second research hypothesis assumed the influence of organic layer's depth on the C balance in the turf grasses. The hypothesis was tested by comparison of C emission/ uptake in turf grasses with 5, 10 and 20 cm depths of organic horizon. We showed that the turf grasses with thick organic layers were more likely to equilibrate the C balance by the third year, compared to more shallow ones. We didn't find any previous research comparing C balance in turf grasses with different depths to validate our findings. However, a thick organic horizon is more preferable to support grass' and roots' growth. In our research the highest biomass increase was shown for the 20TS turf grasses, where 40 % of total biomass was given by roots. This is an evidence of high sustainability of this turf grass soil construction in terms of C balance.

We showed significantly higher biomass and lower soil CO₂ emission for more mature (3 years) turf grasses,

compared to the same turf grasses during the first months after establishment. In the more nature turf, the increased root and grass biomass may result in the positive C balance, as projected by some models (Qian et al. 2003; Zircle et al. 2011). However, this gradual increase of C balance in the turf grasses is possible, when an anthropogenic additions of ‘fresh’ organic material is limited. Such managements are often implemented in greenery practices in Moscow city (Smagin and Sadovnikova 2015) to improve the ornamental quality of the green lawns. As it was clearly shown in our research the ‘fresh’ organic material added to the turf grass systems is easily mineralized and therefore the stabilization of the C balance in these managed turf grasses is unlikely.

Multiple functions of urban turf grasses

Although C-sequestration is important, it is not the only function provided by turf grasses. For example, the ornamental and aesthetic functions and services provided by urban green infrastructure are also highly valued by city-dwellers (Gómez-Baggethun and Barton 2013). High ornamental value was reported for all the three turf grasses based on the projective cover and sprout density, based on the. The highest values obtained for the 20TS confirms that the depth of organic layer is an important factor to support the turf grass’ functioning. The substantial increase in the projective cover and especially in the sprout density during the study, complements the obtained data on C balance to and concludes that the more mature turf grasses perform their functions better compared to those recently established. However, comparatively low ratio of disaccharides in total sugars obtained for all three investigated turf grasses evidences that the vulnerability to stresses is still substantial and turf grasses are not yet sustainable at this stage of their growth.

The obtained results should not be directly extrapolated to the broad range of urban soils, since these turf grasses represent only one type of urban green infrastructure and likely, the most artificial one. However, their role in urban land cover is substantial. For instance, Milesi and Running (2005) showed that turf grasses made up to 40 % of open spaces in cities and covered about 128,000 km² in all US. According to the monitoring of green infrastructure in Moscow in 2014 turf grasses covered around 110 km² (30 % of open spaces) and the municipal greenery programs projected substantial increase of green lawns in the city in coming decade (Kulbachevksy 2015). Therefore, the need for information on functions and services provided by turf grasses is becoming critical.

In our research we focused on C sequestration in turf grasses, since the data limitations constrained the evaluation of other important functions, such as, the, influence on microclimate, and the filtering of surface run-off. However, some judgments can be proposed based on soil temperature and moisture data. The average soil temperature was lower and

the soil moisture was higher in turf grasses compared to the adjacent cropland and the urban forest (Vasenev et al. 2015), which means that there is a high potential that urban turf grasses can mitigate urban heat island effect and store water. Additional research is needed to better investigate these functions of turf grasses, so that their role in the urban ecosystems can be better understood and documented. Turf grasses are artificial ecosystems, since all the stages of their establishment and development are strongly influenced by man. Understanding of the turf grass’s features and functions at the different development stages and under different conditions can provide a relevant tool for their sustainable management.

Conclusion

Urbanization coincides with remarkable expansion of turf grasses (Robbins and Birkenholtz 2003). Therefore the environmental functions of turf grasses, including C sequestration, are getting increasingly important. Artificial ecosystems turf grasses are very vulnerable to anthropogenic and environmental factors and their C stocks and fluxes are not stable especially at the early stages of the turf grass’ development. We clearly demonstrated a substantial CO₂ emission from the turf grasses in Moscow city during the three years after establishment with the largest amount of C lost in the first year. This finding confirms that turf grasses are important sources of biogenic C emissions (Livesley et al. 2010; Sarzhanov et al. 2015), which can be comparable in magnitude to the fossil fuel emissions as was demonstrated by Decina et al. (2016) for the greater Boston area.

Turf grasses substantially contributed C-sources during the first years after establishment, as C uptake by grass and root biomass was limited and therefore did not compensate CO₂ emissions. Although, the total estimated emissions were substantial, gradual changes towards the equilibrium in C balance were found by the end of the observation period. The substantial increase in total biomass and the belowground component, together with the decrease in CO₂ emission, were observed for the third year after turf grass’ establishment. This outcome evidences the possibility for balancing the C uptake and emissions over longer perspective. Positive dynamics in C balance was more evident for the turf constructions with thicker organic layers. The performance of the ornamental function was also positively correlated with the depth of the organic layer. These findings question the existing greenery practice driven by affordability, thus preferencing turf grasses with shallow organic layers. Our study demonstrates high vulnerability of these shallow turf grasses, causing substantial C depletion during the first years after establishment. These findings shall be used to develop guidelines for sustainable turf grass soil construction, which will get essential with increasing urbanization.

Acknowledgments The project was partly supported by Governmental Grant # 11. G34.31.0079 and the Russian Foundation for Basic Research projects # 14-04-31992, 15-34-70003 and 15-54-53117. The authors thank Agata Alunova, Bhoobun Bhavish for collecting field data and Anastasia Lebedeva for the assistance with biomass analysis, Dr. Tatiana Morin, Ellen Moedt and Anna Paltseva for assistance with editing the manuscript.

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