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Short communication

Elevated soil CO_2 efflux at the boundaries between impervious surfaces and urban greenspaces

XiaoGang Wu [a, b], Dan Hu [b, *], ShengLi Ma [b, 1], Xia Zhang [b], Zhen Guo [b, 2], Kevin J. Gaston [c]

[a] College of Urban and Rural Construction, Shanxi Agricultural University, Taigu, Shanxi, China
[b] Research Center of Eco-Environmental Science, Chinese Academy of Sciences, Beijing, China
[c] Environment and Sustainability Institute, University of Exeter, Penryn Campus, Cornwall, United Kingdom

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ABSTRACT

Impervious surfaces and greenspaces have significant impacts on ecological processes and ecosystem services in urban areas. However, there have been no systematic studies of how the interaction between the two forms of land cover, and especially their edge effects, influence ecosystem properties. This has made it difficult to evaluate the effectiveness of urban greenspace design in meeting environmental goals. In this study, we investigated edge effects on soil carbon dioxide (CO_2) fluxes in Beijing and found that soil CO_2 flux rates were averagely 73% higher 10 cm inwards from the edge of greenspaces. Distance, soil temperature, moisture, and their interaction significantly influenced soil CO_2 flux rates. The magnitude and distance of edge effects differed among impervious structure types. Current greening policy and design should be adjusted to avoid the carbon sequestration service of greenspaces being limited by their fragmentation.

1. Introduction

The planet is progressively being ‘paved’ (Elvidge et al., 2007), with the expansion of impervious surfaces representing one of the most extreme anthropogenic modifications of the global environment (Grimm et al., 2008). Surprisingly, however, many of the ecological consequences of this change remain poorly understood (Gaston et al., 2013). This is particularly true for ecosystem processes, which to date in urban areas have received a small fraction of the attention that they have had in other ecosystems (Grimm et al., 2008; Gaston et al., 2013). For example, longstanding assumptions about the levels and distribution of soil organic carbon (SOC) in urban areas have recently been challenged empirically, highlighting the importance of considering carefully whether and how these need to be taken into account in regional and national carbon (C) auditing (Davies et al., 2011; Pouyat et al., 2006). Both the short and the long-term temporal dynamics of organic C in urban systems remain even more poorly understood (Lorenz and Lal, 2009; Zhang et al., 2012; Diaz-Porras et al., 2014).

A particular challenge in understanding ecosystem processes in urban areas, and the influence of impervious surfaces, is the finescale spatial heterogeneity of these systems (Gaston et al., 2013; Mitchell et al., 2015). High numbers of small, and often tiny, patches of greenspace occur in many cities and towns and may in sum contribute as much or more to its overall extent as do any large individual spaces (e.g., 76.7% of greenspace patches in Beijing, China are smaller than 900 m (Grimm et al., 2008)) (Qian et al., 2015). This means that not only are the ecosystem processes of urban areas often dominated or strongly shaped by what happens within small habitat patches, but they are also likely to be powerfully influenced by edge effects between impervious surfaces and these spaces (Gaston et al., 2013). Indeed, one might argue that the ecology of urban ecosystems is foremost that of edge effects, and that more than in any other ecosystem there is a need for finescale studies to understand such effects on ecosystem processes (Gaston et al., 2013; Mitchell et al., 2015).

In this paper, we determine edge effects of impervious surfaces on soil CO_2 fluxes in urban greenspaces. We predicted that fluxes would be greater in the immediate vicinity of the boundaries between impervious surfaces and greenspaces, particularly because of the impacts of the impervious surfaces on heat transfer

* Corresponding author.
E-mail address: hudan@rcees.ac.cn (D. Hu).
[1] Current address: College of Eco-Environmental Engineering, University of Qinghai, Xining, Qinghai, China.
[2] Current address: The First Institute of Oceanography, State Oceanic Administration, Qingdao, Shandong, China.

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(Celestian and Martin, 2004), and that these fluxes would be influenced by the structure of the adjacent impervious surfaces.

2. Methods

This study was conducted in 18 greenspaces in the Xueyuanlu and Aoyuncun, Beijing. The two neighborhoods, which have a mixture of high density residential, commercial and transport infrastructure land use, have been intensively developed in the last decade driven by the construction of facilities for the 2008 Summer Olympic Games. This region has a temperate monsoon-influenced humid continental climate (mean summer temperature, 26.2 °C; mean winter temperature, −3.7 °C; annual precipitation, 601.8 mm, mostly in summer) (Qian et al., 2015). We classified impervious surface types with well-defined structure across the study region into: 1) buildings, generally highly protrude above the ground and root into the soil with some form of foundation; 2) roads and commercial parking lots, their below ground sections ≥60 cm depth; 3) playgrounds, driveways and pedestrian walkways, their below ground sections ≤30 cm depth. Because of the rather low ownership, low stories building were excluded from the sampling buildings list. Potential greenspace sites to be sampled were then identified using the following criteria: the width of adjoining green area was no less than 6 m, there was direct sunlight throughout daytime, and there was a flat and even surface. Additionally, only sites fully covered by turfgrass were selected to minimize the influence of tree root distribution pattern on soil CO_2 flux. Finally, 6 sites were selected for each of the three impervious surface types.

Based on the findings from preliminary experiments, 2 m-long transects were established perpendicular to impervious surface/greenspace boundaries, and extending into the interior greenspace (Fig. 1). The greenspace sites were dominated by short turf grasses (mainly *Poa pratensis* L., *Festuca arundinacea* Schreb. or *Trifolium repens* L.), and sporadically managed (irrigation and mowing) throughout the growing season. All sampled edges had predominantly south-facing aspects and full-length direct sunlight, which we expected to maximize the distance of any edge influence in sunny day. Sampling points were established along each transect at the following distances: 10, 40, 70, 100, 150, and 200 cm (Fig. 1). Three or more parallel transects were used in each site, and all transects were >5 m apart.

Data were collected during autumn (between October and December 2012) and summer time (from June to mid-September 2013) in an attempt to determine the seasonal variation of edge effects. Observations that had missing data were removed from

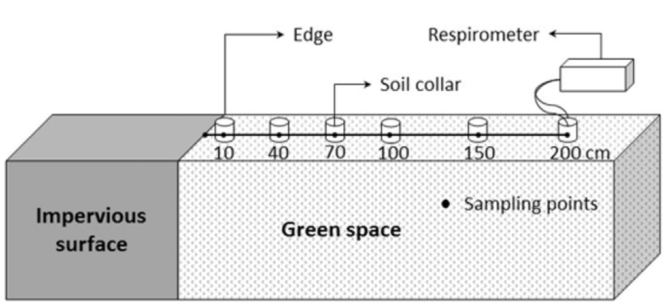

Fig. 1. The transect and instruments configuration. Transects were established perpendicular to impervious surface/greenspace boundaries, and extending into the interior green space. Sampling points were established along each transect at the following distances: 10, 40, 70, 100, 150, and 200 cm. PVC collars (diameter of 20.0 cm and height of 10.0 cm) were inserted into the floor to a depth of 3–4 cm at each sampling point. Soil CO_2 flux rates (RS) were measured using a LI-COR 8100 portable respirometer (LI-COR Inc., Lincoln, NE, USA), consisting of an infrared gas analyzer connected to a 20-cm survey chamber (LI-8100-103, LI-COR Inc.).

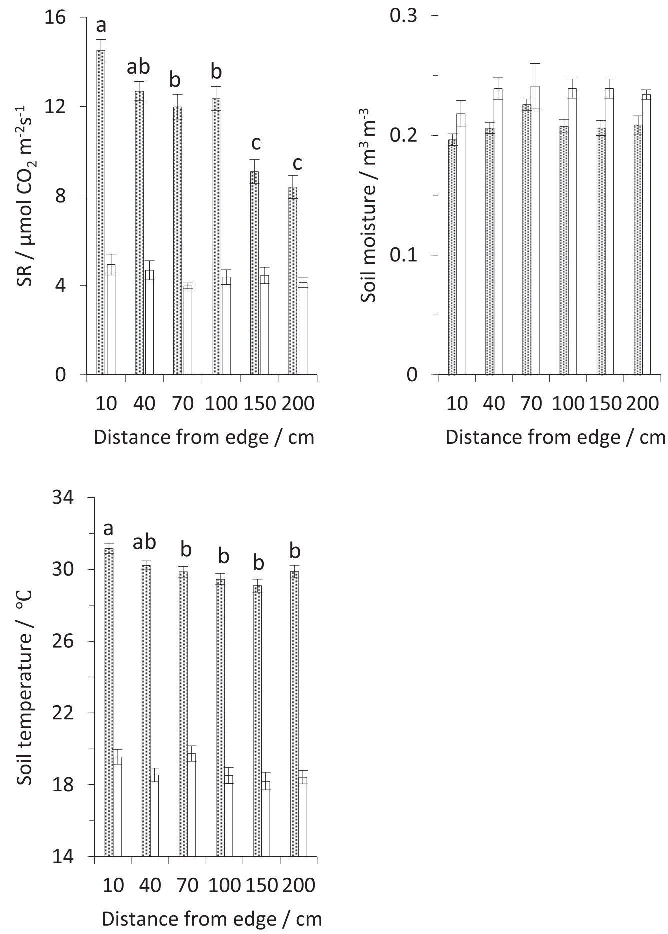

Fig. 2. Soil respiration rate, soil moisture and temperature along the distance gradient from the impervious surface/greenspace boundary. Filled and blank column indicate summer and autumn, respectively. Data are presented as the mean value of all the sampling plots. Letters a, b and c designate values that were significantly different from the others.

further analysis. Finally, 16 and 77 transects were measured in autumn and summer respectively, and a similar number of transects were allocated to each surface types. We measured soil CO_2 flux rate (R_S) along the transects (from 10 cm to 200 cm inwards) on sunny days using a LI-COR 8100 portable respirometer (LI-COR Inc., Lincoln, NE, USA), consisting of an infrared gas analyzer connected to a 20-cm survey chamber (LI-8100-103, LI-COR Inc.). R_S (expressed as μmol CO_2 m^{-2} s^{-1}) were computed using the LI-8100 file viewer application software (FV8100, LI-COR Inc.). The soil temperature (T_S) and soil moisture (W_S) at 5 cm depth next to the respirometer chamber were recorded simultaneously during respiration measurements using a thermal probe (LI-8100-201 Ω, Type E, LI-COR Inc.) and a moisture probe (LI-8100-202 EC-5, Decagon Devices, Inc., Pullman, WA) connected to the LI-8100 system. Three replicate measurements of R_S were made at each sampling point during each measurement campaign. Each campaign was carried out during 11:00 a.m. -15:00 p.m. local time, assuming there was smallest air temperature variation during the day. Moreover, data were collected unless no management activities or rain happened within 48 h.

The magnitude of edge influence (MEI) was calculated using the equation MEI $= (e - i)/(e + i)$ (e = value of the R_S at the edge, i = value of R_S in the interior greenspace), as recommended by Harper et al. (2005) (Harper et al., 2005). The distance of edge influence (DEI) was defined as that at which the mean value was

Table 1
Results from two-way permutation ANOVA analyses of the effect of distance, type, and their interaction on soil CO_2 efflux.

Source	Mean sq	df	Denominator df	F. value	Pr (>|F|)
Ts	4.72	1	1193.8	20.8	5.62e-06***
Ws	3.81	1	1190.5	16.81	4.41e-05***
Ts: Ws	5.33	1	1202.6	23.52	1.40e-06***
Distance	10.22	5	1201.9	45.08	2.20e-16 ***
Type	0.53	2	9.7	2.35	0.15

Significant codes: '***' 0.001 '**' 0.01 '*' 0.05. *Ts*: soil temperature; *Ws*: soil volumetric water content.

significantly different from the reference value (Harper et al., 2005). Data from 200 cm from the edge were used as reference values (interior greenspace). We used a linear mixed-effects model, implemented with the lme4 package in R (R-CoreTeam), to identify the main and interactive effects on R_S of *Ts*, *Ws*, impervious surface type and distance. We designated sampling site as a random effect. We used Tukey's HSD multi-comparison test to detect differences between distance gradients. Statistical analysis was carried out using R 3.1.0 open source software (Bates et al., 2014). Parenthetically reported errors are standard errors; R_S data were log-transformed to achieve normal distribution.

3. Results and discussion

As expected, the mean R_S and T_S diminished with distance from the impervious surface into the greenspace in summer (Fig. 2), showing obvious edge effects across the impervious space/greenspace boundary. The highest value of R_S was observed at the edge (10 cm), which was 73% ($P < 0.001$) higher than that at the reference point (14.5 ± 0.5 versus 8.4 ± 0.5 μmol CO_2 m^{-2} s^{-1}, Fig. 2). The R_S values at 40–100 cm were 43%–51% higher than the reference point ($P < 0.001$, Fig. 2). However, neither R_S nor T_S exhibited any significant edge effects in autumn (Fig. 2). T_S was significantly higher 10 cm from the impervious space/greenspace boundary in summer, but there was no difference at other measuring points (Fig. 2, $P < 0.05$). For R_S and T_S, there was no significant difference between the point at 40 cm and other points within 100 cm from the edge. But, dramatic decline of R_S occurred at 150 cm in summer (Fig. 2). Both in summer and autumn, W_S showed irregular variation along the transects. ANOVA analysis indicated that T_S, W_S, the $T_S \times W_S$ interaction, and distance from the edge had significant effects on R_S, but the types of impervious surface did not (Table 1). The precise mechanism of the much higher soil-surface CO_2 efflux from the edge has not yet been determined, however, a likely driver is soil temperature (Fig. 2, Table 1).

Edge influence, as summarized by MEI scores (Table 2), exhibited a declining trend with distance for three types of impervious surfaces. There were obvious differences in the magnitude and distance of edge influence for the three types. Within 0–100 cm, playgrounds, driveways, and pedestrian walkways exhibited a much higher edge influence than did roads and commercial parking lots, and high buildings showing the lowest values. Compared with R_S at 200 cm (reference point), the MEI from the playgrounds, driveways and pedestrian walkways at 10 cm was more than twice that from high buildings. The set of distances for DEI were 10–100 cm, 10–70 cm, and 10–70 cm for playgrounds, driveways and pedestrian walkways, high buildings and roads and commercial parking lots, respectively. The strongest impact on soil temperature was shown by roads and commercial parking lots, followed by playgrounds, driveways, and pedestrian walkways, and there was no significant difference for high buildings. This might be one of the reasons that contributed to obvious variation in MEI among types. Roads and commercial parking lots were characterized with deeper below ground bases, which could have enhanced transfer and accumulation of heat from sun radiation. Thus, higher temperatures and soil CO_2 flux rates than the others were observed (Table 2). Extremely high MEI for playgrounds, driveways, and pedestrian walkways might partly be due to CO_2 flow from the soil beneath the impervious cover (Table 2). Moisture, nutrients, and oxygen are still available in soil under pavement (Viswanathan et al., 2011). As a result, some grass roots and associated microorganisms can horizontally expand into the soil under playgrounds, driveways and pedestrian walkways (≤30 cm), which are characterized by shallower underground section. The upward CO_2 efflux out of the root zone is blocked, leading to accumulation of high concentrations of CO_2 and then lateral diffusion (Viswanathan et al., 2011).

Although highly simplistic, and taking no account of likely soil physicochemical traits which are important in various C process, and many other factors (e.g. species composition, planting history, management activities) (Lorenz and Lal, 2009), those findings indicate that up to a distance of 100 cm from the edge, soil CO_2 flux rates was much higher than those of the interior greenspace. The results imply that the more edges, the more CO_2 efflux there will be.

Table 2
Mean values (±SE) of the soil temperature, moisture, and respiration rate at different distances from the impervious surface/greenspace boundary in summer.

Response variable	Distance from the edge (cm)						DEI (cm)
	10	40	70	100	150	200	
Roads, commercial parking lots							
Ts, °C	33.8 ± 0.5^a	33.2 ± 0.4^a	32.0 ± 0.4^{ab}	31.8 ± 0.4^{ab}	31.2 ± 0.4^b	32.3 ± 0.3^b	
Ws, %	18.5 ± 1.1^c	19.3 ± 1.2^{bc}	19.9 ± 1.0^{bc}	24.2 ± 1.0^a	23.8 ± 1.1^{ab}	26.4 ± 1.3^a	
R_S, μmol CO_2 m^{-2} s^{-1}	19.3 ± 1.3^a	18.9 ± 1.2^a	19.2 ± 1.3^a	15.2 ± 1.3^{ab}	13.5 ± 1.3^b	10.8 ± 1.2^b	10–100
MEI	0.28	0.27	0.28	0.17	0.11		
Playgrounds, driveways and pedestrian ways							
Ts, °C	30.0 ± 0.3^a	29.4 ± 0.3^a	28.5 ± 0.5^a	27.6 ± 0.5^b	27.7 ± 0.8^b	28.6 ± 0.8^a	
Ws, %	19.3 ± 0.8^{ab}	20.5 ± 0.72^a	21.6 ± 1.08^a	20.2 ± 1.4^{ab}	19.7 ± 1.45^{ab}	15.71 ± 1.28^b	
R_S, μmol CO_2 m^{-2} s^{-1}	15.2 ± 0.8^a	12.4 ± 0.6^b	13.8 ± 0.8^{ab}	12.2 ± 0.8^b	6.1 ± 0.4^c	5.7 ± 0.4^c	10–100
MEI	0.45	0.37	0.41	0.36	0.03		
Buildings							
Ts, °C	30.2 ± 0.5^a	29.4 ± 0.5^a	29.0 ± 0.5^a	28.9 ± 0.5^a	28.1 ± 0.624^a	28.0 ± 0.6^a	
Ws, %	21.0 ± 0.7^{ab}	21.6 ± 0.6^a	21.8 ± 0.6^a	21.6 ± 0.6^a	18.4 ± 0.744^b	18.7 ± 0.8^b	
R_S, μmol CO_2 m^{-2} s^{-1}	11.2 ± 0.4^a	9.3 ± 0.3^b	9.18 ± 0.43^b	8.5 ± 0.4^{bc}	7.1 ± 0.3^c	7.6 ± 0.3^{bc}	10–70
MEI	0.19	0.10	0.10	0.06	−0.03		

Notes: Magnitude of edge influence (MEI) was calculated as $(e - i)/(e + i)$, where e = value of the R_S at the edge, i = value of the R_S in the interior greenspace (200 cm); the magnitude of EI thus varies between −1 and + 1 and is equal to 0 when there is no EI. Distance of edge influence (DEI) was defined as the distance for which the mean value was significantly different from the reference value [13]. Superscript letters (a, b, and c) designate value that were significantly different from the others ($p < 0.01$).

In the context of the high fragmentation of green spaces in Beijing, with a landscape shape index of 297 [10], which means 16,600 km of boundaries for the 186 km (Grimm et al., 2008) of green space, there will be a huge potential resultant reduction of C emission. If all of the patches smaller than 500 m (Grimm et al., 2008) (67% of the patches in Beijing in 2009) were expanded to 2900 m^2 (average patch size) (Qian et al., 2015), and one assumes these were square, then there would be a 14.4% reduction in CO_2 efflux.

4. Conclusion

To the best of our knowledge, this is the first study to examine the impact of impervious surfaces on soil CO_2 flux across the boundary of greenspace. Our data showed a potentially large and previously unmeasured soil CO_2 efflux from greenspace/impervious surface boundaries that are now generally distributed across urban areas. Soil CO_2 flux changes resulting from impervious surfaces fundamentally differ from urban heat islands in that their effects are limited to microscale (<2 m) and are only exhibited in summer time. Future studies that continuously observe soil surface CO_2 efflux in control sites might reveal greater mechanistic insights about soil CO_2 flux edge effects. Municipalities have been focusing efforts on developing techniques and approaches to achieve more efficient and sustainable cities. Studies that integrate biogeochemical processes into designing and implementing ecosystem-services-based green spaces are of critical importance (Pataki et al., 2011).

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