

**Diurnal, weekly, seasonal and spatial variabilities in
carbon dioxide flux in different urban landscapes in
Sakai, Japan**

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Abstract

To evaluate CO₂ emissions in urban areas and their temporal and spatial variabilities, continuous measurements of CO₂ fluxes were conducted using the eddy covariance method at three locations in Sakai, Osaka, Japan. Based on the flux footprint at the measurement sites, CO₂ fluxes from the three sites were partitioned into five datasets representing a dense urban center, a moderately urban area, a suburb, an urban park, and a rural area. Distinct biological uptake of CO₂ was observed in the suburb, urban park, and rural areas in the daytime, whereas high emissions were observed at dense and moderate urban areas in daytime. Weekday CO₂ emissions in the dense urban center and suburban area were approximately 50% greater than during weekend and holidays, but the other landscapes did not exhibit a clear weekly cycle. Seasonal variations in the urban park, rural area, and suburban area were influenced by **photosynthetic uptake**, exhibiting the lowest daily emissions or even uptakes during summer months. In contrast, the dense and moderately urban areas exhibited higher emissions in winter and summer months, when emissions significantly increased as air temperature increased in summer and air temperature decreased in winter. Irrespective of the landcover type, all urban landscapes measured in this study acted as net annual CO₂ sources, with emissions ranging from 0.5 to 4.9 kg C m⁻² yr⁻¹. The magnitude of the annual CO₂ emissions was negatively correlated with green fraction; areas with a smaller green fraction had higher annual CO₂ emissions. Upscaled flux estimates based on the green fraction indicated that the emissions for the entire city were 3.3 kg C m⁻² yr⁻¹, which is equivalent to 0.5 Tg C yr⁻¹ or 1.8 Mt CO₂ yr⁻¹ based on the area of the city (149.81 km²). A network of eddy covariance measurements is **useful for characterizing spatial and temporal variations in net CO₂ fluxes from urban areas. Multiple methods would be required for evaluating rationale behind the fluxes and overcoming the limitations in future.**

1. Introduction

Cities emit a considerable amount of carbon dioxide (CO₂) that is associated with human activities into the atmosphere (Canadell et al., 2007). Urban areas account for only a small percentile of the earth's land surface but emit 30–50% of total anthropogenic CO₂ (Mills, 2007; Stetterthwaite, 2008). Consequently, CO₂ emissions from cities are highly heterogeneous at spatial and temporal scales.

Global CO₂ emissions have often been estimated using inventories based on point source database, statistics for national and regional CO₂ emission, and satellite remote sensing (Oda and Maksyutov, 2011). The major challenge for estimating global CO₂ emissions is to understand the spatio-temporal dynamics of CO₂ emissions in various cities. Because emissions data are used in top-down estimates of global CO₂ budget (Peters et al., 2007; Schmel et al., 2001), a better estimate of CO₂ emissions from cities will improve our understanding of global carbon cycle, including terrestrial and ocean fluxes.

To evaluate CO₂ emissions in cities and their temporal and spatial variabilities, continuous measurements of CO₂ fluxes have been conducted using the eddy covariance method in various urban landscapes, including dense urban built-up area (Gioli et al., 2012; Grimmond et al., 2002, 2004; Kotthaus and Grimmond, 2012; Nimitz et al., 2002; Pawlak et al., 2011; Velasco et al., 2005), suburban areas (Bergeron and Strachan, 2011; Coutts et al., 2007; Crawford et al., 2011; Hirano et al., 2015; Moriwaki et al., 2006; Ward et al., 2013), urban parks (Kordowski and Kuttler, 2010), and urban forests (Awal et al., 2010), in several cities. These results indicated that cities emit a considerable amount of CO₂ into the atmosphere associated with human activities, such as vehicle traffic and household heating in the wintertime. Even in urban parks, CO₂ was emitted to the atmosphere due to human activities (Kordowski and Kuttler, 2010). Magnitude of CO₂ emissions and its temporal variabilities depended on the cities, associated with type of contributed human activities under different climate conditions (Järvi et al., 2012; Moriwaki et al., 2006; Velasco et al., 2016; Ward et al., 2013, 2015), and role of urban vegetation (Awal et al., 2010; Kordowski and Kuttler, 2010; Peters and McFadden, 2012; Ward et al., 2015), showing considerable heterogeneities.

Multi-site eddy covariance towers were used to synthesize the data and showed that green fraction was the index explaining spatial variability in annual CO₂ emissions (Nordbo et al., 2012; Velasco and Roth, 2010; Ward et al., 2015) because green fraction possibly has many factors determining CO₂ emission: greater green fraction relates a lesser road and population density (Nordbo et al., 2012). Upscaling can provide a high-resolution map of direct CO₂ emissions from cities. Previous studies have examined the relationship between annual CO₂ emissions and green fraction at a global scale (Nordbo et al., 2012; Velasco and Roth, 2010; Ward et al., 2015). It is unclear whether upscaling CO₂ emissions is possible within a city, because multi-site eddy covariance measurements within a city are often unavailable.

In this study, we present diurnal, weekly, seasonal, and spatial variabilities in CO₂ flux continuously measured at three different locations within 5 km of each other in Sakai, Osaka, Japan. Considering flux footprint, the data represent five urban landscapes, including a dense urban center, a moderately urban area, a suburb, a rural area, and an urban park. Regardless of the landscape type, all landscapes emitted considerable CO₂ annually with different temporal metabolisms, providing a useful overview of anthropogenic CO₂ emissions.

2. Materials and methods

2-1. Study sites

Sakai is the second largest city in Osaka Prefecture, located in western Japan. The population was approximately 842,000 in 2015. Because the city is located on the eastern shore of Osaka Bay, sea breeze circulation is evident throughout the year except when seasonal winds are not strong. The area is on a uniformly flat plane; the north-south and the east-west slopes are 0.0030° and 0.0024°, respectively. The climate of Sakai is temperate; the mean annual air temperature is 15.9°C, the maximum monthly mean air temperature is 28.0°C in August, the minimum monthly mean air temperature is 5.2°C in January, and the mean annual precipitation is 1187 mm yr⁻¹ between 1981 and 2010 according to the Japanese Meteorological Agency.

The Sakai city center (SAC) site (Fig. 1; Table 1) is located on a tower at the top of a

city office building (34°34'25"N, 135°28'80"E). The population density around the city center is approximately 12150 km⁻², based on the Japanese Government Statistics. The area is a densely built-up urban area with a mean building height of 10.7 ± 3.1 m. Since the distributions of building heights were highly skewed in low-height buildings, the mean building height greater than 20 m was 36 m, which occupied 33% of the total building area. Many arterial roads and two highways with heavy traffic are present within the flux footprint. Because industrial and commercial areas are located in the western and northern parts of the city, those areas are expected to show higher rates of human activity than locations where residential areas are dominant.

The Oizumi Ryokuchi urban park (IZM) site (Fig. 1; Table 1) is located at the northern end of the city (34°33'48"N, 135°32'1"E), and was established in 1972. The measurements were conducted at a tower located at the east edge of the park. Because of the consistent presence of a sea breeze, the tower is mostly located downwind direction of the park during the daytime. The landcover of the park consists of 51% trees, 15% grassland, and 34% other, such as ponds, buildings, pavement, and bare ground. No vehicle traffic was allowed in the park except parkings. Measurements using a plant canopy analyzer (LAI-2000, LI-COR, Lincoln, Nebraska, USA) showed that the leaf area index of trees ranged from 3.2 to 5.7 m² m⁻² with a mean of 4.3 m² m⁻² in the summer months. The mean and maximum tree height was estimated 12.3 ± 4.1 m and 21 m, respectively, using a digital surface model by Google Earth. The area surrounding the IZM is a mixed landscape of residential area and agricultural fields and is characterized as a rural area (Table 1). The population density of surrounding residence of IZM is approximately 7940 km⁻², based on the Japanese Government Statistics.

The Osaka Prefecture University (OPU) site (Fig. 1; Table 1) is located at the west edge of Osaka Prefecture University (34°32'50"N, 135°30'10"E). Because the measurements were conducted at the roof top of a building, the flux footprint represents only a small suburban area. The western part of the site contains a protected forest on a kofun (the ancient burial mound), Mozu Kofungun. The area is characterized as a suburb, consisting of a university, a residential area, small streets, a graveyard, and trees. The mean and maximum tree height was 13.1 ± 2.9 m and 19 m, respectively, and the mean and

maximum building height are 9.1 ± 2.9 m and 15 m, respectively.

2-2. Observations

We measured CO₂ fluxes using the eddy covariance method at the three sites. For SAC, a sonic anemometer (SAT550, Sonic Corp., Tokyo, Japan) and an open-path infrared gas analyzer (LI-7500, LI-COR) were installed on a 16-m tower located at the top of the city office building (111 m above the ground) at the end of November, 2009. For IZM, a sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) and an open-path infrared gas analyzer (EC150, Campbell Scientific Inc.) were installed 30 m above the ground on a tower at the end of January 2015. For OPU, sonic anemometers and several infrared gas analyzers were installed on a 2-m mast above the rooftop at the edge of the building (16.2 m above the ground) in November 2014. Turbulent fluctuations were recorded at 10Hz using a datalogger (8421, Hioki, Japan) for SAC and a datalogger (CR1000, Campbell Scientific Inc.) for IZM and OPU.

For the OPU site, eddy covariance systems were periodically changed. A sonic anemometer (DA600, Sonic Corp.) was in place from November 2014 to March 2015 and again in November 2015. A different sonic anemometer (Model 81000, R. M. Young, Traverse, Michigan, USA) was in place from March 2015 to April 2015, and a third type of sonic anemometer (Windmaster, Gill Instruments, Lymington, UK) was in place in April 2015. The eddy covariance system was initially a closed-path system using a gas analyzer (LI-6262, LI-COR), until March 2015, and was then changed to an open path system using an open-path infrared gas analyzer (LI-7500, LI-COR). Another eddy covariance system using a sonic anemometer (DA600, Sonic Corp.) and an open-path infrared gas analyzer (LI-7500, LI-COR) was installed on a different edge of the building in November 2015. This additional measurement system increased data acquisition, because we eliminated the data coming from the roof. Consequently, CO₂ fluxes were calculated based on the different systems with relevant corrections. We confirmed that there was no significant difference between open-path and closed-path systems through an inter-comparison ($RMSE = 2.18 \mu\text{mol m}^{-2} \text{s}^{-1}$; $F_{\text{open}} = 1.00 * F_{\text{closed}} - 0.03 \mu\text{mol m}^{-2} \text{s}^{-1}$; $R^2 = 0.84$; F_{open} and F_{closed} represent CO₂ fluxes by the open and closed paths), but these

flux measurements have higher uncertainties than those from the other sites.

Meteorological and environmental variables were measured at each site. Air temperature, relative humidity, and incoming solar radiation were measured at the three sites. Rainfall, atmospheric pressure, incoming longwave radiation, and ground heat fluxes at the top of the building were measured at OPU. Leaf area index was manually measured approximately once a month using a plant canopy analyzer (LAI-2000, LICOR) at ten forested sectors in IZM.

2-3. Data analysis

In this study, we used one-year eddy covariance data measured at 2015 at SAC and OPU and the period from February 2015 to January 2016 at IZM. Turbulent fluxes were calculated using the eddy covariance method using the Flux Calculator program (Ueyama et al., 2012). Before the half-hourly covariance of vertical wind velocity and scalar quantities was calculated, spike data were removed from the raw data. No trend removal was applied. The artificial fluctuations of sonic air temperature associated with water vapor were corrected. Vertical wind velocity was coordinated as mean vertical wind velocity was zero using the double rotation method. The angle-of-attack errors for the Gill Instruments and R. M. Young anemometers were corrected based on Nakai and Shimoyama (2012) and Kochendorfer et al. (2012), respectively. The high-frequency loss for line averaging and sensor separation was corrected using theoretical transfer functions for the open-path systems (Massman, 2000) and empirical transfer functions for the closed-path system (Moore, 1986). Air density fluctuations were corrected based on Webb et al (1980).

Filtering nighttime data using friction velocity (u_*) threshold was not applied in this study. This was because (1) no clear threshold was obtained in nighttime data, (2) data coverage at night was small due to the limited flux footprint, and (3) sensible heat fluxes in summer months often showed positive values even at night except IZM. Our handling of nighttime data was the same in previous studies in urban areas (e.g., Liu et al., 2012), but a potential underestimate of nighttime fluxes may have occurred. The storage term was added to the turbulent fluxes for the vegetative site (IZM), whereas the storage was

not considered for urban sites (SAC and OPU). The storage term for IZM was estimated based on CO₂ concentrations at the height of the eddy covariance measurement.

Flux data were selected for each landscape after a quality test and footprint analysis. First, we applied the quality test to remove half-hourly flux data that included noise based on a criterion (Appendix B.1 in Ueyama et al., 2012). A stationary test, integral turbulence test, and higher moment test were applied, since flow statistics did not strongly differ with ideal surfaces (Kaimal and Finnigan, 1994); σ_w/u^* at neutral conditions were 1.3 for SAC, 1.5 for OPU, and 1.3 for IZM; σ_u/u^* at neutral conditions were 2.6 for SAC, 2.6 for OPU, and 3.2 for IZM, where σ_w and σ_u are the standard deviation of vertical and horizontal wind velocities. Half-hourly data were subdivided into 5 minutes, and then covariance was calculated for each 5-minute data. If difference between mean of covariance for the subdivided classes and half-hourly covariance was greater than 40% of half-hourly covariance, data was rejected as instationary (Foken and Wichura, 1996). We rejected the data when turbulent intensity was greater than 50% for IZM and 200% for SAC and OPU those predicted by the similarity theory. According to the high moment test (Vickers and Mahrt, 1997), we removed data when the absolute value of skewness was greater than 3.6 or when the value of kurtosis was greater than 14.4. The fluxes, measured when winds came from the tower directions, were also removed. For OPU, the fluxes, measured when winds came from the directions of the building, were removed as well. For SAC, based on a footprint model (Kormann and Meixner, 2000), we rejected a data, when the source area contributing 80% of the flux footprint contained sea and mountains. Similarly, for IZM, we rejected flux data, when the source area contributing 50% of the flux footprint exceeded the boundary of the urban park. Displacement height was estimated based on MacDonald et al. (1998) for SAC, whereas those for other sites were estimated 0.7 times of the mean building or tree heights.

Depending on wind directions, flux data at IZM and SAC were divided into two data series. For IZA, flux data from the west represented the urban park, whereas data from other directions represented the rural area consisting of mixed residential and agricultural areas (Fig. 1). For SAC, flux data from the west represented the densely built-up urban center, whereas data from other directions represented the moderate urban to residential

area (Fig. 1). Here, we defined the moderate urban as green fraction of 27%, which was double compared with those at dense urban built up (Table 1). Consequently, we formed five flux datasets from measurements at the three sites in the year of 2015 for SAC and OPU and in the period from February 2015 to January 2016 in IZM: a dense urban center (west SAC), a moderately urban area (east SAC), a suburb (OPU), an urban park (west IZM), and a rural area (east IZM). Data coverage was 11% in west SAC, 21% in east SAC, 31% in OPU, 16% in west IZM, and 13% in east IZM.

Partitioning CO₂ fluxes into gross photosynthetic and respiratory fluxes was conducted only for the west and east IZM and OPU datasets, because apparent daytime uptake were measured. The flux partitioning was conducted using the Flux Analysis Tool program (Ueyama et al., 2012). First, the relationship between nighttime CO₂ fluxes and air temperature was established based on a model (Lloyd and Taylor, 1994). The relationship was determined daily with a 49-day moving window. Gross photosynthetic flux were calculated as the difference between the estimated respiratory flux and the measured CO₂ flux. Because the estimated respiratory fluxes consisted of biological fluxes and nighttime anthropogenic fluxes, it is important to note that the estimated gross photosynthetic fluxes did not truly represent gross primary productivity, which is often used in ecosystem studies (e.g., Baldocchi, 2008).

Gaps in the five datasets were filled using the Flux Analysis Tool program. First, small data gaps for periods less than 2.0 h were filled by linear interpolation. Second, for the west and east IZM datasets, gaps were filled using a combination of look-up-table and non-linear regression methods (Ueyama et al., 2012), an approach well established for use in natural ecosystems (Ueyama et al., 2013). For data gaps from west and east SAC and OPU, mean diurnal variations were applied, in which a mean diurnal pattern was created daily using a 51-day moving window. Two mean diurnal patterns were created, one for weekdays and once for weekends and holidays according to the weekly cycle.

2-4. Upscaling using GIS data

The annual CO₂ flux was upscaled according to the relationship between annual fluxes and green fraction. The green fraction was estimated using a green census data developed

by government of Sakai City. The green census data were created using high-resolution aerial photographs from August 2001 consisting of polygons of approximately 5-m spatial resolution. Based on the high-resolution polygon data, the green fraction was evaluated at a 500-m spatial resolution. Because the green census data often classified water area as green area, we masked water area using landcover data based on a geographical information system (Digital Map 5000 for the Kinki region in 2008 by the Geospatial Information Authority of Japan).

3. Results

3-1. Diurnal variations

CO₂ fluxes showed distinct diurnal variation (Fig. 2). At the IZM, in the urban park and rural area, distinct biological signals were observed, representing apparent daytime uptake. The magnitude of the daytime uptake was stronger in the urban park than in the rural area. A daytime uptake was also observed at OPU in the summer months from April to August. In contrast to the apparent biological signals, diurnal variations at SAC showed greater CO₂ emissions during the daytime than at night. Emissions were greater in the dense urban center (west SAC) than in the moderately urban area (east SAC). Emissions from the urban areas tended to be high in the daytime, particularly in the morning rush hours. Such diurnal variations were similar to those for traffic counts measured by highway exits within the flux footprint (Fig. 2b). Note that the traffic counts at the exits peaked in the evening, whereas those at the entries could peaked in the morning (data are not shown).

3-2. Seasonal variations

Different urban landscapes showed different seasonal variations in CO₂ flux (Fig. 3). Similar to the diurnal variations, distinct biological signals were observed at IZM in the urban park and rural area. The daily mean CO₂ flux showed lower emissions with occasional negative values during summer months in both IZM sites. The suburban site of OPU generally showed CO₂ emissions throughout the seasons, but the emissions rate tended to be lower in the spring than in other months. The SAC site showed high CO₂

emissions throughout the seasons, and higher emissions were observed in the dense urban center than in the moderately urban area. The seasonal variations in SAC exhibited two distinct peaks during the summer and winter periods.

The seasonal variations in the daily CO₂ flux were dependent on daily mean air temperature and exhibited different patterns in different landscapes (Fig. 4). For the urban site of SAC, CO₂ emissions increased as temperatures decreased ($0.46\text{--}0.27 \text{ g C m}^{-2} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$; $p < 0.1$) when mean daily temperature less than 10°C. Higher CO₂ emissions were also observed at higher temperatures at SAC. An increase in CO₂ emissions at higher temperatures was also observed at OPU. Gas consumption by university buildings within a footprint of OPU was consistent with the two seasonal peaks revealing higher consumption in the summer and winter months (Fig. A1). In the urban park and rural area, CO₂ emissions decreased as temperatures increased above 15°C: $-0.27 \text{ g C m}^{-2} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$ for IZM park ($p < 0.01$) and $-0.13 \text{ g C m}^{-2} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$ for IZM rural ($p < 0.01$) when mean air temperatures were greater than 15°C (Fig. 4).

Gross photosynthetic fluxes were greater in summer months than in winter months (Fig. 3). Surprisingly, the gross photosynthetic fluxes in the urban park and OPU were comparable, probably due to contributions of trees around the university and from the kofun at OPU. The gross photosynthetic fluxes for the rural area were approximately half those for the urban park and OPU. The gross photosynthetic fluxes increased as temperatures increased higher than 20°C at $0.15\text{--}0.38 \text{ g C m}^{-2} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ($p < 0.01$).

3-3. Weekly variations

Among the five landscapes, distinct weekly cycles of CO₂ emissions were only observed at the west SAC and OPU sites (Fig. 5). On average, CO₂ emissions on weekdays were approximately 50% greater than emissions on weekends and holidays ($p < 0.01$) at the west SAC and OPU sites, even though the weekday CO₂ flux at the east SAC was 10% higher than the fluxes on holidays ($p < 0.01$). The greater emissions on weekdays were consistently observed throughout all seasons, and were consistent with the traffic counts from the highway exits, where traffic was approximately 23% higher on weekdays than on weekends and holidays (Fig. 2b).

3-4. Annual CO₂ balance and its spatial variations

All urban landscapes measured in this study acted as net CO₂ emissions sources on the annual timescale (Fig. 6; Table 2). The strength of the annual CO₂ emissions was negatively correlated with the green fraction ($R^2 = 0.96$; $p < 0.01$); areas of a smaller green fraction had higher annual CO₂ emissions. The annual CO₂ emissions estimated in this study were lower than those examined using a global synthesis by Nordbo et al. (2012) (Fig. 6).

Based on the significant relationship between the green fraction and the annual CO₂ flux, annual CO₂ fluxes were upscaled to the city scale (Fig. 7). Because the green fraction of Sakai was low in the north and high in the south (Fig. 7a), annual CO₂ emissions were greater in the north than the south (Fig. 7b). The annual CO₂ fluxes from the entire city were 3.3 kg C m⁻² yr⁻¹, which corresponds 0.5 Tg C yr⁻¹ or 1.8 Mt CO₂ yr⁻¹ based on the area of the city (149.81 km²). The estimated emissions were lower than an inventory-based estimate from 2000 to 2012 (8.0 ± 0.6 Mt CO₂ yr⁻¹) published by the government.

4. Discussion

Annual CO₂ emissions from Sakai City ranged in those measured in other studies, but tended to be at the lower end of the range (Fig. 6). For the same fraction of green area (in this case, the green fraction was less than 20%), urban emissions ranged from 4 to 18 kg C m⁻² yr⁻¹ for other cities (Nordbo et al, 2012; Velasco and Roth, 2010). CO₂ emission in our city was lower than those measured at urban centers: a dense urban built-up in London (12.7 g C m⁻² y⁻¹; Ward et al., 2015), historical city center in Florence (8.3 g C m⁻² y⁻¹; Gioli et al., 2012), and residential area of south central Vancouver (6.7 g C m⁻² y⁻¹; Christen et al., 2012). The annual emissions in our city were also lower than previous cities that had a similar population density; there were only two cities whose population was higher than our city, but the annual emissions in our city was 7th in the global synthesis (Fig. 12b in Ward et al., 2015). The low CO₂ emissions rate in Sakai City was evident in daytime peaks during winter months (Fig. 2) compared with a dense urban built-up in London (e.g., more than 50 μmol m⁻² s⁻¹, Ward et al., 2015) and a low built up

in Beijing ($30 \mu\text{mol m}^{-2} \text{s}^{-1}$, Liu et al., 2012). Warmer winter temperatures may contribute to lower emissions as a result of reduced building heating and thus lower annual emissions in Sakai City compared with other northern cities. The annual emissions rate in our urban center was comparable to that of the densely populated residential area in Yoyogi, Tokyo ($4.3 \text{ kg C m}^{-2} \text{yr}^{-1}$, Hirano et al., 2015), and Kugahara, Tokyo ($3.4 \text{ kg C m}^{-2} \text{yr}^{-1}$, Moriwaki and Kanda, 2004).

The sensitivity of the CO_2 emissions to cold temperatures was comparable to that described in the previous studies (Bergeron and Strachan, 2011; Liu et al., 2012; Pawlak et al., 2011). The effect of building heating has often been estimated as a slope between air temperature and the CO_2 emissions rate: $-2.02 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ in London (Ward et al., 2015), $-0.21 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ in Łódź (Pawlak et al., 2011), and $-0.35 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ in Beijing (Liu et al., 2012). These values are comparable to those obtained in our city: $-0.37 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ for all SAC ($p = 0.03$) and $-0.27 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ for east SAC ($p < 0.01$) when mean air temperatures were less than 15°C (Fig. 4), even though an insignificant correlation was obtained for west SAC. No sensitivities to cold temperatures were found in the urban park (west IZM), rural area (east IZM), or residential area (OPU), could be due to the mixed effects of biological and anthropogenic signals.

CO_2 emissions in urban landscapes (SAC and OPU) also increased as temperatures increased in the summer months (Fig. 4): $0.22 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ in west SAC ($p = 0.01$), $0.24 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ in east SAC ($p = 0.02$), and $0.13 \text{ g C m}^{-2} \text{d}^{-1} \text{ }^\circ\text{C}^{-1}$ in OPU ($p = 0.26$). Because traffic did not show a clear seasonal variation (Fig. 2b), the reason for this increase is unclear, but one possibility is the contribution of emissions from gas-powered air conditioners (Fig. A1). The prevalence rate of gas-powered air conditioners is approximately 20% of non-residential buildings, based on an assessment by the Japan Gas Association. The water vapor flux in the summer months also significantly increased above a mean daily air temperature of 17°C (T. Ando, unpublished data), suggesting gas consumption by air conditioners. Kanda et al. (1997) also measured the high water vapor flux in a summer at an urban center, Tokyo, and suggested that gas consumption associated with cooling towers. In contrast to residences, tall buildings often used gas-based air conditioners, including the Sakai city office and buildings at OPU; especially

after the Fukushima nuclear disaster at 2011, nuclear power plants for studies area did not operate. Consequently, gas-based air conditioners increased (Agency for Natural Resources and Energy, 2015). A weaker dependence in OPU probably occurred because emissions from gas-powered air conditioners from the university building were canceled out by an increase in biological uptake (Fig. 3b). The sensitivity of gross photosynthetic fluxes to warming temperatures was $0.38 \text{ g C m}^{-2} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$ in OPU ($p < 0.01$).

Weekly cycles of CO_2 emissions were only observed at urban sites (Fig. 5), representing the strength of human activities. Previous urban CO_2 flux studies reported that major contributors to anthropogenic emissions were vehicle emissions and gas consumption (Gioli et al., 2012; Hirano et al., 2015; Velasco et al., 2005; Ward et al., 2013). Velasco and Roth (2010) indicated that weekly cycles were primarily related to vehicle emissions. Traffic count was high on weekdays at SAC (Fig. 2b), and business offices including the university are often more active on weekdays than weekends and holidays. In contrast, there were no clear weekly cycle urban parks, and rural areas. Larger differences between weekday and holiday in west SAC and OPU suggest the greater contributions of emissions from vehicles and business offices compared with other landscapes. This underscores the importance of temporal variations in CO_2 emissions by land use.

The urban park acted as a net annual CO_2 source despite of abundant vegetation. Several factors explain the annual emissions from the urban park. First, the urban park frequently suffered from various management activities, such as harvesting and weeding. Such frequent disturbances could decrease sink and increase source (Gough et al., 2007; Latty et al., 2004). Warmer climates in the urban area may induce higher respiration (Awal et al., 2010). A limited footprint might influence CO_2 fluxes arising from emissions from surrounding areas. We re-checked the data selection using stricter criteria according to which we rejected data when 80% of the flux footprint exceeded boundary of the urban park, but the results were almost the same. A positive CO_2 budget of $2400 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ was previously measured at an urban park in Germany (Kordowski and Kuttler, 2010).

Partitioning flux data measured at a single site with distinct landscapes is a useful approach in urban flux studies. CO_2 fluxes at different landscapes measured at a single

site showed considerably different behaviors (Fig. 2, 3, 6). The approach previously used for clarifying variations in fluxes in different landscapes involved single flux measurements (Järvi et al., 2012; Kordowski and Kuttler, 2010; Hirose et al., 2015). The partitioning concurrently contained limitations that data availability decreases with partitioning. In the study area, sea-breeze circulation was dominant in the summer months, resulting in a large data gap from certain wind directions (shown in section 2-3). Accumulating long-term data could be useful for filling the data gap.

The green fraction can be useful for upscaling annual CO₂ flux in urban area (Fig. 6). The applicability of the green fraction was previously reported based on a global synthesis based on the eddy covariance measurements in urban areas (Nordbo et al., 2012; Velasco and Roth, 2010; Ward et al., 2015); the green fraction as an index of human activities (Nordbo et al., 2012). The relationship between the annual CO₂ flux and the green fraction in Sakai City tended to be lower than the relationship revealed by the global synthesis (Nordbo et al., 2012) (Fig. 6). This difference might indicate that the relationship differs in each city or country. Other environmental variables, such as biomass density (Velasco et al., 2016), might improve the scaling CO₂ fluxes at various cities. Consequently, to quantify the effects of the green fraction on CO₂ emissions in various cities, further direct measurements of CO₂ flux at various urban sites are required.

Upscaled annual CO₂ fluxes for the city (Fig. 7) were lower than estimated using the inventory published by the government. According to the inventory, approximately 57% of CO₂ emissions were associated with the industrial sector, but there was no eddy covariance site in the coastal industrial region. Part of the discrepancy occurred because our upscaling estimated the net flux of urban emissions and vegetative uptake, whereas the inventory quantified the emissions. Hirano et al. (1996) estimated that vegetation in Sakai, primarily in southern sectors, absorbed 0.87 Mt CO₂ yr⁻¹ of CO₂ based on an inventory-based estimates. Another reason for the discrepancy was that our estimate did not include hot spot emissions, such as power plants and incineration facilities, or non-CO₂ gas emissions. Oda and Maksyutov (2011) estimated that approximately half of annual total CO₂ emissions were from point sources in most countries. Because our upscaled CO₂ flux did not include such point sources, CO₂ emissions from point sources

could be more rigorously quantified using the governmental inventory than non-point sources (Oda and Maksyutov, 2011). Thus, upscaled CO₂ flux could be useful as an additional constraint, providing more information regarding CO₂ emissions from non-point sources. Since our simple method potentially contained uncertainties associated with limited number of one-year eddy covariance sites, and only consideration of green fraction, the estimates should be improved with further eddy covariance sites and additional environmental variables for explaining CO₂ fluxes.

Inherent limitations associated with the eddy covariance method at the urban environment must be reduced and quantified in future studies. The measurements height at SAC was more than ten times higher than the mean building height, although reducing the height was restricted due to sporadic tall buildings. This could induce underestimates of nighttime fluxes (Oke, 2006), and thus the annual emission could be underestimated. CO₂ storage within the building was not considered in our study, but must be important in late afternoon and early morning (Vogt et al., 2006). In contrast, the measurements height at OPU was within the roughness sublayer (1.2 to 1.7 times the mean building and tree heights), and thus fluxes were influenced by localized near fields (Oke, 2006). Separating wind sectors using the footprint analysis may suffer uncertainties when advection was triggered by wind shifts.

5. Conclusion

Based on continuous measurements using the eddy covariance method at three different urban sites, diurnal, weekly, seasonal, and spatial variabilities in CO₂ flux were evaluated in Sakai, Osaka, Japan. The urban center and university sites acted as CO₂ sources throughout seasons. A clear weekday/holiday cycle of CO₂ emissions was observed at those sites. A diurnal pattern in the urban center was correlated with those for traffic count. High emissions were observed in the urban site in both winter and summer months, even though the traffic did not change seasonally, suggesting that changes in gas consumption influenced the seasonal variabilities. The urban park and rural area exhibited CO₂ uptake during summer months, with distinct daytime uptake. Regardless of the green fraction, all landscapes considered in this study acted as an annual CO₂ source. Previous studies of

the relationship between annual CO₂ emissions and the green fraction for a wide spectrum of global cities (Nordbo et al, 2012; Velasco and Roth, 2010) revealed slightly differing patterns from that observed in our city. Consequently, the relationship based on eddy covariance data within a single city could be useful to evaluate CO₂ emissions at the city scale. The network of eddy covariance measurements within a city is useful for characterizing spatial and temporal variations in net CO₂ fluxes from urban areas.

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Figure and table captions:

Figure 1. Aerial photograph by Google Earth showing the study area, where the 80% flux footprint in daytime is shown with red lines. The boundary of Sakai City is shown as a yellow line.

Figure 2. Mean diurnal variations of (a) CO₂ fluxes and (b) traffic count at two highway exits within the flux footprint of SAC west. The diurnal patterns were created every consecutive three months in 2015. Because measurements at IZM began in February 2015, diurnal variations for IZM during the period from January to March were calculated based on data from February and March in 2015 and January in 2016.

Figure 3. Seasonal variations of daily mean (a) CO₂ fluxes and (b) gross photosynthetic flux in 2015, shown as a 7-day running mean.

Figure 4. Relationship between daily mean air temperature and daily mean CO₂ flux; CO₂ flux data were binned with 3°C intervals.

Figure 5. Averaged daily CO₂ flux for each day of the week in 2015 for (a) SAC west and (b) OPU; fluxes for holidays were separately averaged. Vertical lines represent standard deviation.

Figure 6. Relationship between annual CO₂ flux (F_{CO_2}) and green fraction (f_G). The solid line represents regression based on our flux data for Sakai, and the dashed line represents a relationship based on a global synthesis (Nordbo et al., 2012).

Figure 7. Spatial distributions of (a) green fraction and (b) upscaled net CO₂ flu in Sakai City. The green fraction was calculated for a 500-m spatial resolution based on an inventory of green spaces.

Figure A1. Seasonal variations in monthly gas consumption rates at Osaka Prefecture University for 2015. The data are shown for 16 buildings in the west-sector of the university, where flux measurements were conducted, and for four buildings located within the flux footprint.

Table 1. Landcover fraction within daytime flux footprint. Landcover classification was conducted using the Digital Map 5000 for the Kinki region in 2008 by the Geospatial Information Authority of Japan, and the green space fraction was based on a green census by the government of Sakai City. Because the landcover classification and green space are different data sources, the sum of each fraction often exceeds 100%. The daytime flux footprint was calculated using the analytical footprint model ([Kormann and Meixner, 2000](#)), and median values in 2015 were classified for sixteen direction ([Fig. 1](#)).

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| | SAC west | SAC east | OPU | IZM park | IZM rural |
|--|----------|----------|-----|----------|-----------|
| | % | % | % | % | % |
| Residence | 27 | 9 | 9 | 1 | 15 |
| Commercial, industrial, and public offic | 34 | 38 | 69 | 6 | 15 |
| Road | 27 | 29 | 10 | 3 | 6 |
| Green space | 14 | 27 | 44 | 72 | 62 |

Table 2. Annual CO₂ fluxes from the eddy covariance measurements and upscaled city-scale flux.

| Site | CO ₂ flux g C m ⁻² yr ⁻¹ |
|-----------|--|
| SAC west | 4948 |
| SAC east | 3134 |
| OPU | 1270 |
| IZM park | 802 |
| IZM rural | 495 |
| Upscale | 3325 |

Figure 1

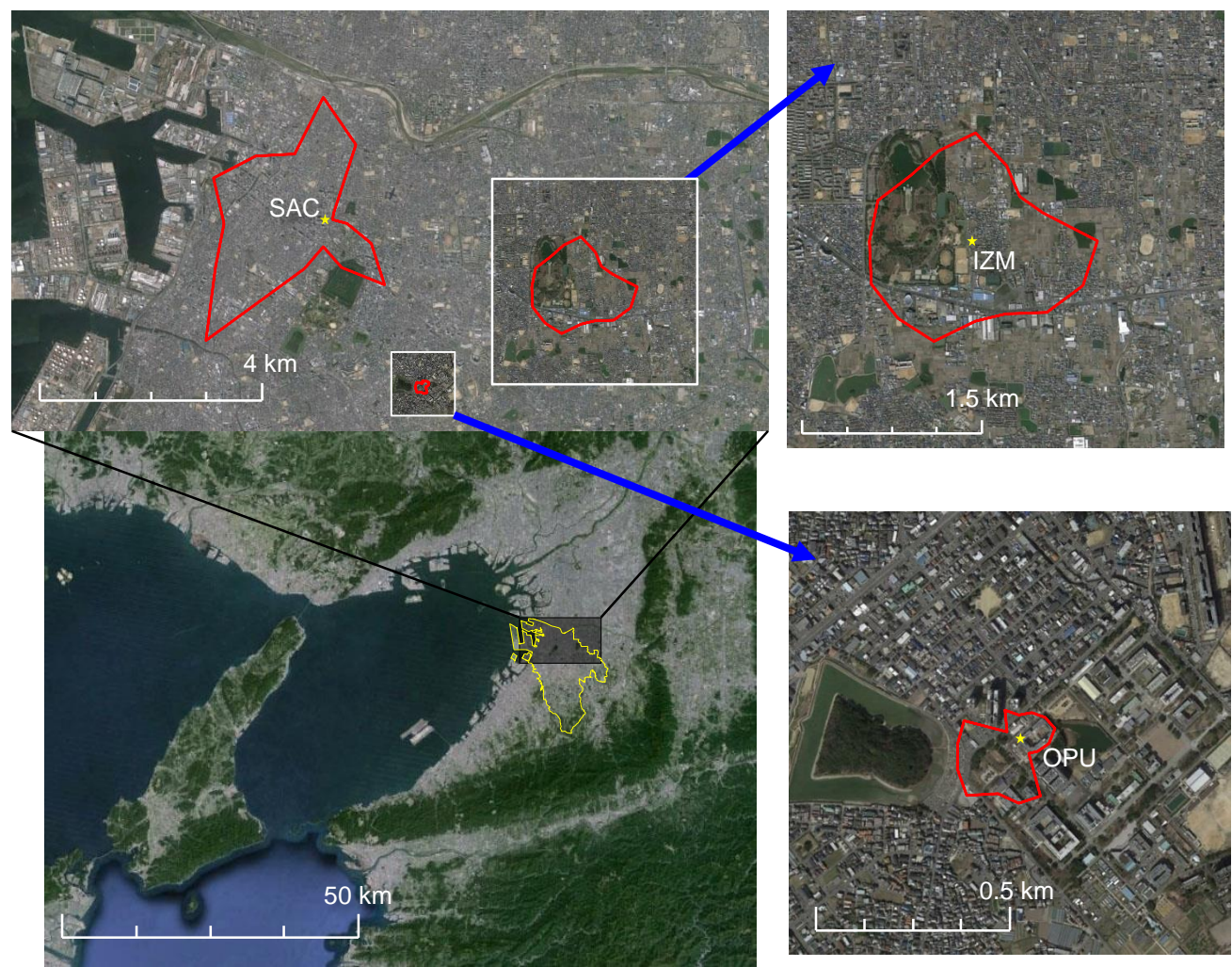


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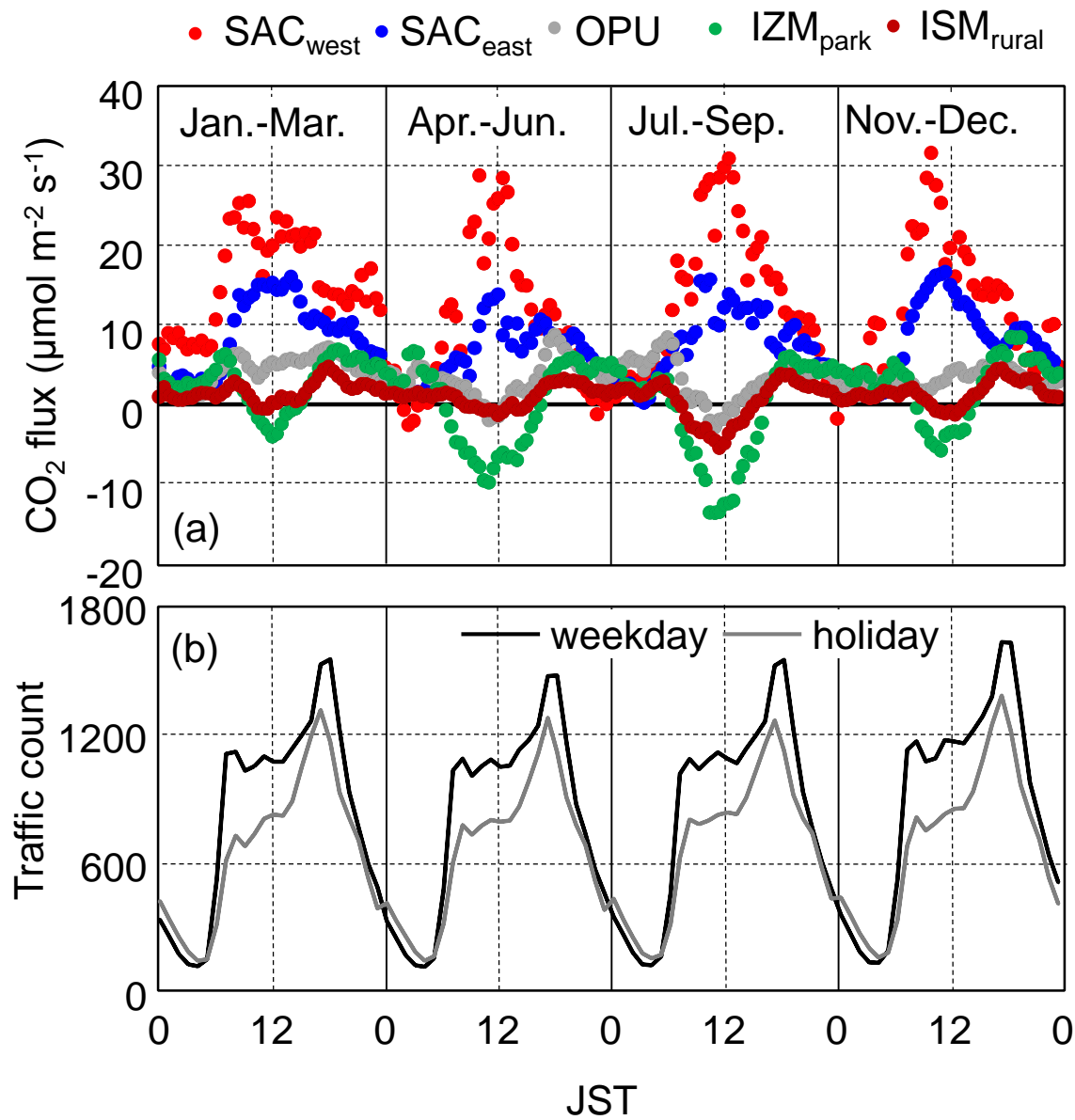


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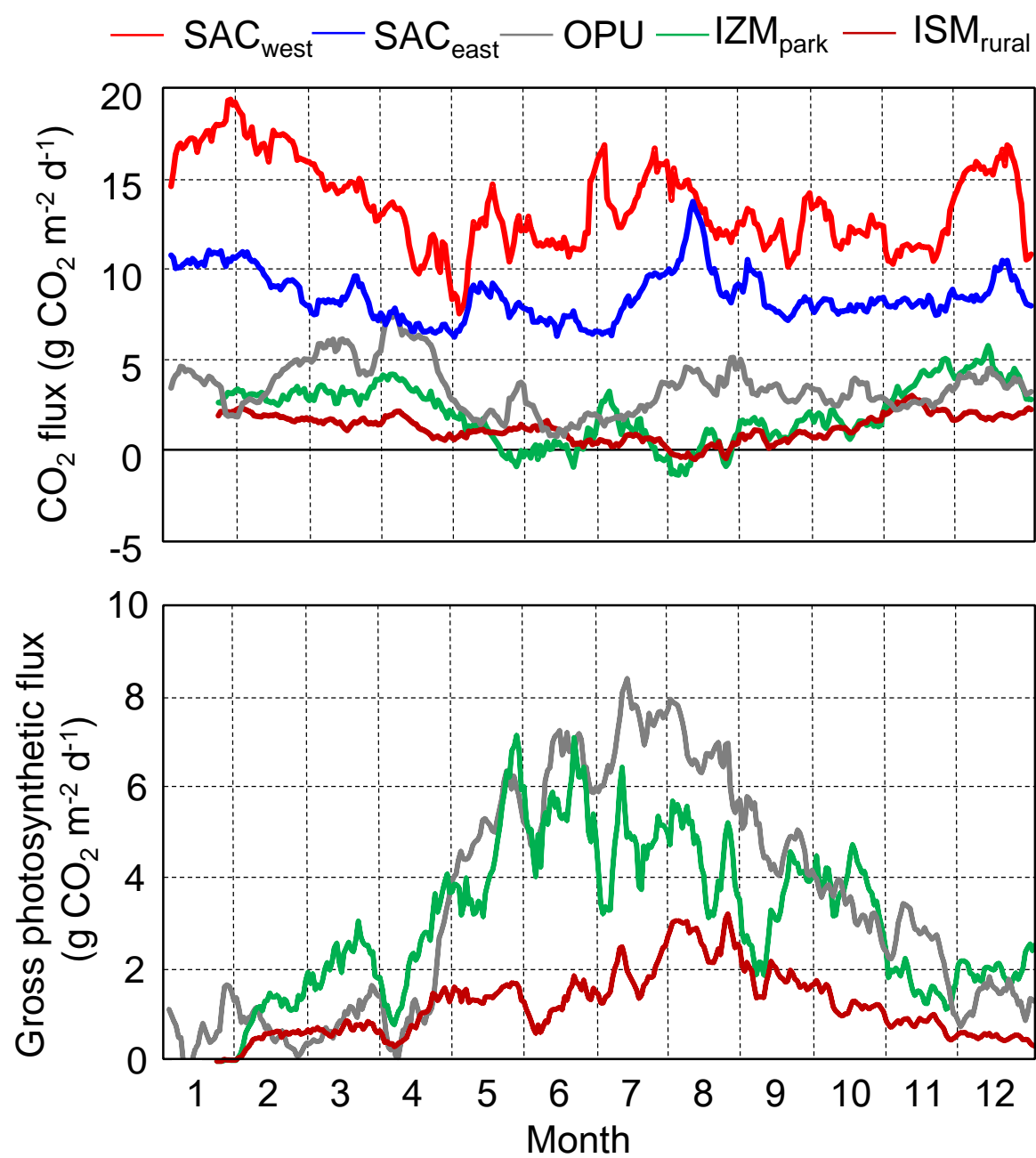


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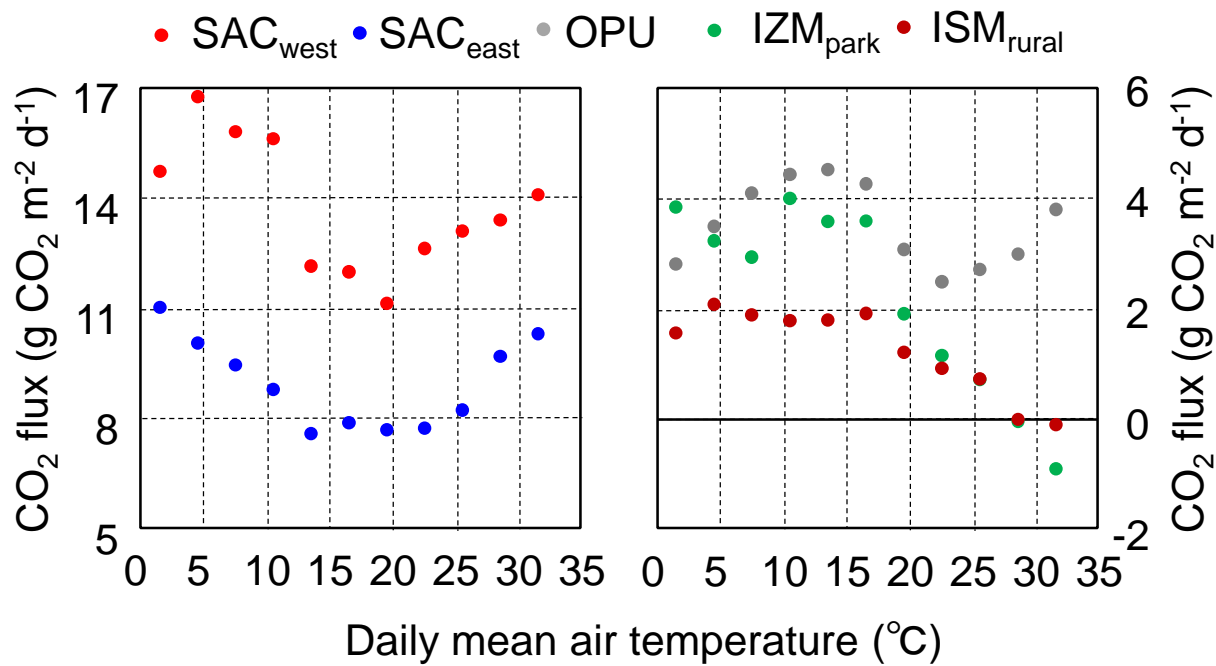


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Figure 5

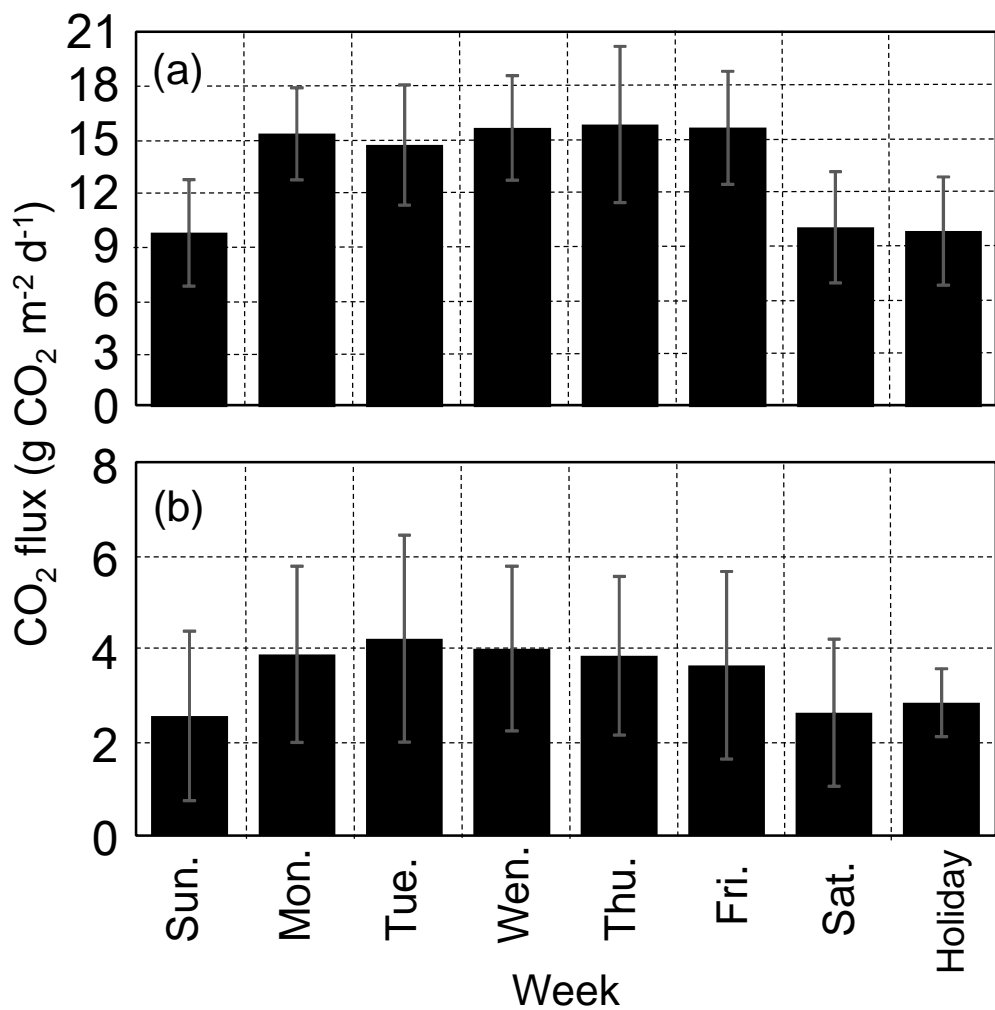


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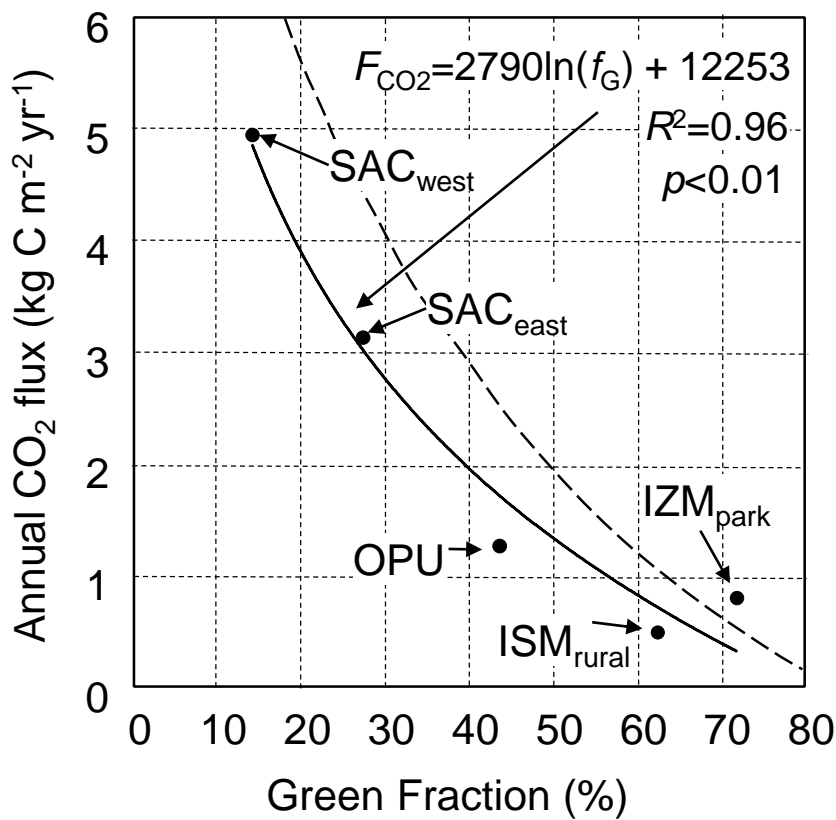


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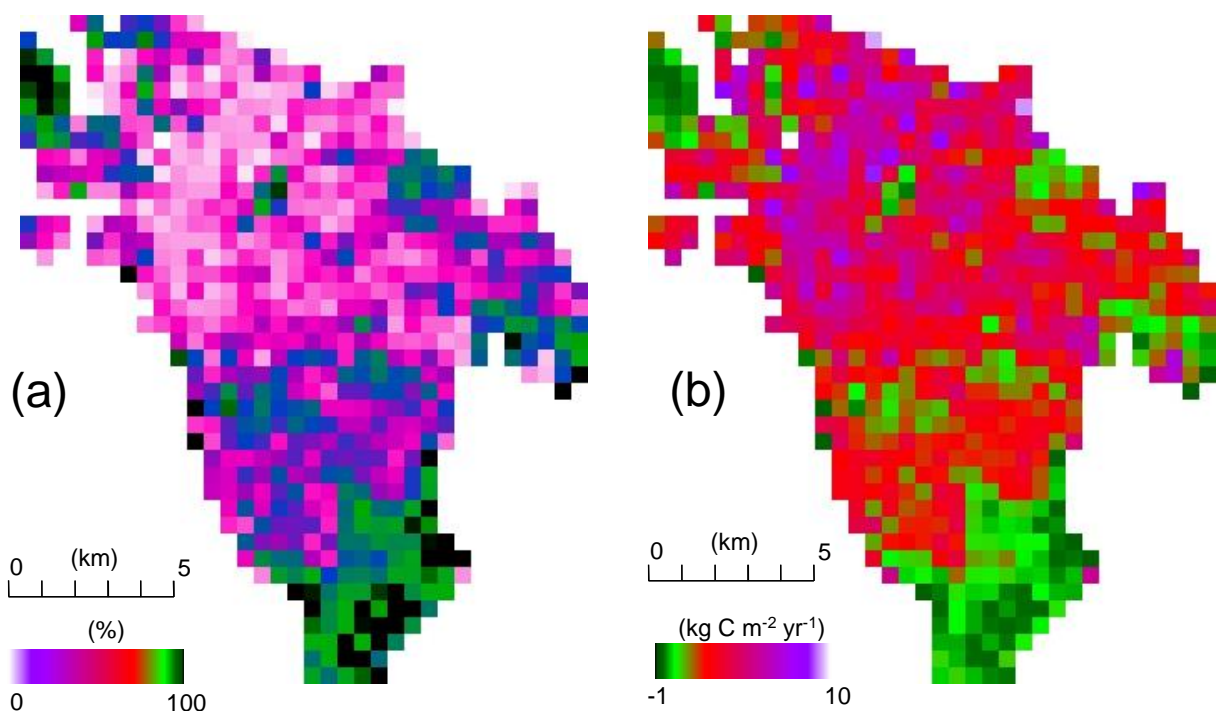


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Appendix

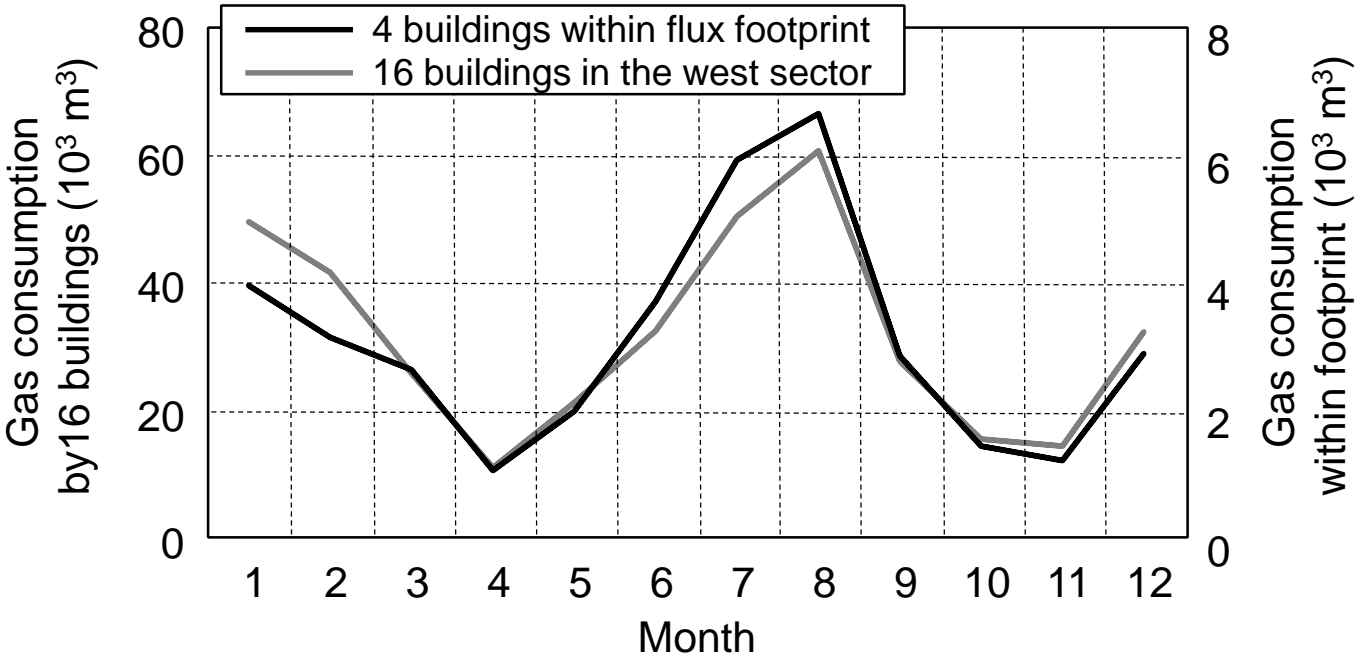


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