

Interpreting CO₂ Fluxes Over a Suburban Lawn: The Influence of Traffic Emissions

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Abstract Turf-grass lawns are ubiquitous in the United States. However direct measurements of land–atmosphere fluxes using the eddy-covariance method above lawn ecosystems are challenging due to the typically small dimensions of lawns and the heterogeneity of land use in an urbanised landscape. Given their typically small patch sizes, there is the potential that CO₂ fluxes measured above turf-grass lawns may be influenced by nearby CO₂ sources such as passing traffic. In this study, we report on two years of eddy-covariance flux measurements above a 1.5 ha turf-grass lawn in which we assess the contribution of nearby traffic emissions to the measured CO₂ flux. We use winter data when the vegetation was dormant to develop an empirical estimate of the traffic effect on the measured CO₂ fluxes, based on a parametrised version of a three-dimensional Lagrangian footprint model and continuous traffic count data. The CO₂ budget of the ecosystem was adjusted by 135 g C m⁻² in 2007 and by 134 g C m⁻² in 2008 to determine the natural flux, even though the road crossed the footprint only at its far edge. We show that bottom-up flux estimates based on CO₂ emission factors of the passing vehicles, combined with the crosswind-integrated footprint at the distance of the road, agreed very well with the empirical estimate of the traffic contribution that we derived from the eddy-covariance measurements. The approach we developed may be useful for other sites where investigators plan to make eddy-covariance measurements on small patches within heterogeneous landscapes where there are significant contrasts in flux rates. However, we caution that the modelling approach is empirical and will need to be adapted individually to each site.

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1 Introduction

The recent decades have seen large increases in the extent of urban and built-up land use. From 1982 to 1997, built-up areas increased by 37% in the United States and they are projected to increase by another 79% by 2025 (Alig et al. 2004), with much of the growth in suburban areas (Kahn 2000). Although European cities traditionally have been much more compact, their built-up area has also increased, by 20% from 1980 to 2000 (European Commission 2006). Urbanised areas represent a major source of CO₂ to the atmosphere due to the concentration of human activities that depend on energy from fossil-fuel combustion. At the same time, many built-up areas, especially suburban land-use types, contain significant amounts of vegetation that takes up CO₂ by photosynthesis and releases it through metabolic activity. Against this background, there has been increasing interest in measuring land–atmosphere fluxes of CO₂ in different types of urban settings (e.g. Grimmond et al. 2002; Nemitz et al. 2002; Soegaard and Moller-Jensen 2003; Moriwaki and Kanda 2004; Vogt et al. 2006; Coutts et al. 2007; Schmidt et al. 2008; Vesala et al. 2008).

Suburban areas in the United States are often dominated by single-family detached houses surrounded by turf-grass lawns, trees, and other green spaces. Milesi et al. (2005) estimated that cultivated turf grasses covered 163,800 km² of the continental United States, which would represent a large potential area for CO₂ exchange. However, direct measurements of land–atmosphere fluxes using the eddy-covariance method above lawn ecosystems are difficult due to the typically small dimensions of lawns and the heterogeneity of land use in an urbanised landscape. For example, in suburban Minneapolis–Saint Paul, Minnesota, our study site surrounding the KUOM tall tower had 34% cover of turf-grass lawns within a residential area of 4 km². However, there was only one lawn of sufficient size for eddy-covariance measurements that was not a sports field or golf course, neither of which would be suitable for the long-term installation of micrometeorological instruments. Given the typically small patch size of urban turf-grass lawns, there is the potential that CO₂ fluxes measured above them may be influenced by nearby CO₂ sources such as passing traffic.

Many neighbourhood-scale studies show that traffic is an important source of short time scale variations in CO₂. Grimmond et al. (2002) implicitly state that the CO₂ flux largely depends on emissions of fixed (industrial, commercial, institutional) and mobile (traffic) sources, in addition to the variations in vegetation cover. To separate the fluxes originating from different land surfaces and mobile sources requires highly detailed information about the spatial distribution of the sources and sinks, as well as the spatial extent of the flux source area, or footprint. For this reason, previous studies have used approaches such as wind sector analysis of surfaces such as park versus main traffic route (Nemitz et al. 2002; Vesala et al. 2008; Burri 2009) or have installed multiple towers in different areas of the city (Coutts et al. 2007). In order to verify such top-down approaches to separating the sources and sinks of CO₂, smaller, ecosystem-scale flux measurements can be of potential benefit. At the scale of a single turf-grass lawn, we can assume horizontal homogeneity and often a flat surface. However, there is the potential that CO₂ from traffic sources located beyond the upwind fetch of the turf-grass field could affect the measured fluxes. In this respect, the problem that sources from outside of an ecosystem of interest may influence the measured fluxes is also

common to natural or managed ecosystems that normally occur in small patches, e.g. in the Arctic tundra (McFadden et al. 1998), at mountainous sites (Hammerle et al. 2007; Hiller et al. 2008), or at single agricultural field (Ammann et al. 2007).

In this study, we show that even when the flux footprint was mainly within a turf-grass field and the CO₂ fluxes followed expected ecological patterns, a very small contribution from traffic CO₂ emissions introduced a bias in the annual carbon budget. We analysed winter data when the vegetation was dormant to develop an empirical estimate of the traffic effect on the measured CO₂ fluxes, based on the footprint model of Kljun et al. (2004) and continuous traffic count data. As a check on the magnitude of the traffic flux predicted by our empirical model, we used published emission factors (INFRAS 2004) to independently estimate the amount of CO₂ released by passing traffic. These analyses also provided us with a unique means of assessing the performance of the footprint model that was roughly analogous to a tracer experiment, but using a long-term site where the well-defined traffic source represented a natural tracer (e.g. Foken and Leclerc 2004; Göckede et al. 2005).

2 Methods

2.1 Site Description

The study site was located in a first-ring suburb of Minneapolis–Saint Paul, Minnesota, USA (44°59′42″N 93°11′11″W, 300 m a.s.l.). We made eddy-covariance measurements of CO₂, water vapour, energy, and momentum exchanges over a 1.5 ha turf-grass field (Fig. 1) from November 2005 to May 2009. For the present study, we analysed data from 2007 and 2008 since continuous traffic counts were available for those years. The dominant species

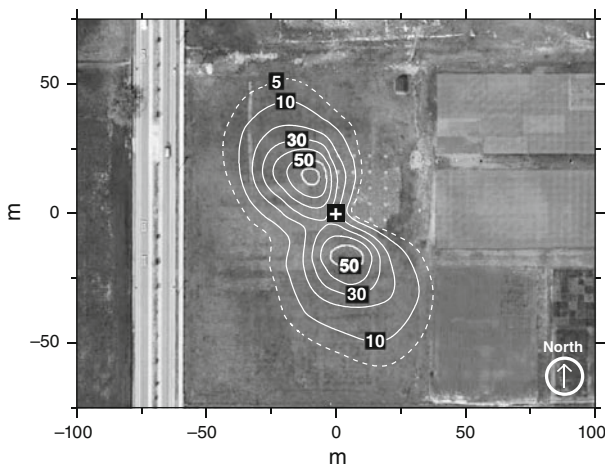


Fig. 1 Aerial photograph of the turf-grass flux site (U.S. Geological Survey, 2004) with the footprint climatology. The white lines are isopleths indicating land areas having the same relative contribution to the measured fluxes, averaged cumulatively over all valid measurements during 2007 and 2008. Solid lines represent 10% contour intervals and the dashed line indicates the 5% isopleth. Even though the footprint climatology does not intersect with the road, individual 30-min footprints (not shown) will. The white cross indicates the position of the flux tower. Areas to the east of the flux tower were behind the instrument array and included irrigated experimental plots of turf grass and some small maple tree saplings; these wind sectors were screened out of our analyses

at the site were the C₃ cool-season turf grasses, Kentucky bluegrass (*Poa pratensis* L.), tall fescue (*Festuca arundinacea* Schreb.), and perennial ryegrass (*Lolium perenne* L.). The site was representative of low-maintenance lawns in the area, such as those found in residential neighbourhoods or a city park. The site was not irrigated and received one application of fertiliser per year. During the growing season (mid-April to mid-October), the grass was mowed weekly to a height of 70 mm, and the clippings were left in place to decompose. A two-lane county road carrying primarily commuting traffic ($\approx 10,000$ vehicles day⁻¹) was located on the western edge of the turf-grass field, at a distance of 60 m from the tower (Fig. 1). The surrounding landscape was a residential neighbourhood consisting of single-family detached houses with a golf course located across the road to the west of the turf-grass study site.

Minnesota exhibits a continental climate, characterised seasonally by different air masses. Cold polar air can intrude in any season, most frequently in the winter. Conversely, both wet and dry subtropical air masses move in from the south mainly in summer (Seeley and Jensen 2006). The mean air temperature (based on the period 1971–2000) is -10.5°C in January and 22.9°C in July (NCDC 2003). The mean annual precipitation is approximately 750 mm, peaking in the summer months when thunderstorms are common (NCDC 2003). The average snow cover in January and February is about 0.10–0.15 m (Minnesota State Climatology Office), but varies widely within the season and among years. Depending on the air temperature and the thickness and composition of the snow pack, the soil freezes to a depth >0.05 m for at least part of the winter.

2.2 Instrumentation

CO₂ fluxes were measured at 1.35 m above the ground using an eddy-covariance system consisting of a CR5000 data-logger, a CSAT3 sonic anemometer (both Campbell Scientific, Inc., Logan, Utah, USA) and an open-path infrared gas analyser (IRGA) (LI-7500, LI-COR, Inc., Lincoln, Nebraska, USA). The measurement height was not adjusted during winter for changes in snow depth because the open site was often wind blown, and snow accumulation was generally low. Soil temperature was recorded at two locations at 0.05 m below ground (STP1, Radiation and Energy Balance Systems, Inc., Seattle, Washington, USA). The incident photosynthetically-active photon flux density (PPFD) was measured at 2 m above the ground (LI-190SA, LI-COR, Inc., Lincoln, Nebraska, USA).

2.3 Data Processing

Fluxes were calculated using a slightly modified version of the *eth-flux* program developed by Werner Eugster (<http://www.ipw.agrl.ethz.ch/~eugsterw/eth-flux/index.html>). This program was part of the CarboEurope software intercomparison (Mauder et al. 2008), and we added a new spike filter to the software, following Vickers and Mahrt (1997). Using a 300-s point-to-point moving window, values exceeding the mean by ± 6 standard deviations (σ) were removed. The maximum number of consecutive spikes was set to five, and the procedure was repeated up to three times for each 30-min block of data. Prior to running *eth-flux*, raw data records were screened and replaced by missing values if the instrument flags were high or if the measurements exceeded the instrument range, indicating measurement problems. Fluxes were computed over 30-min periods by applying a time lag if needed, and calculating the covariance between the vertical wind speed and the scalar, e.g. the CO₂ concentration, using the block averaging method.

High-frequency losses in the fluxes were corrected using Moore's (1986) transfer functions for line averaging (sensible heat flux) and additionally sensor separation for the water

vapour and CO₂ fluxes, with the resulting correction factor trimmed to a maximum of 1.5. The sonic temperature was corrected following Schotanus et al. (1983) and corrections for density effects were made following Webb et al. (1980). No adjustment for self-heating of the LI-7500 (e.g. Burba et al. 2008) was applied because we did not observe systematic apparent net CO₂ uptake during winter and because of the uncertainty of the empirical corrections due to their dependence on the tilt angle of the LI-7500, the wind direction, and the wind speed. The CO₂ flux was corrected for changes in storage in the air column below the sensor by calculating the change in the CO₂ concentration measured by the LI-7500 over each 30-min period.

Before further analysis, we screened out periods with wind directions from 016° to 135°, a wind sector that included experimental and irrigated lawn patches that were located behind the eddy-covariance tower (see Fig. 1). We screened out precipitation events using measurements from a rain gauge at a weather station located 750 m away from our study site, and also we removed records when the path of the IRGA was obscured (automatic gain control >69). Outliers were detected using a day-to-day running window of 13 days if the point occurred outside the mean $\pm 3\sigma$. This screening was done separately for daytime and nighttime data. Using the algorithm of Gu et al. (2005), a low u_* (friction velocity) threshold of 0.06 m s^{-1} was determined. Data were removed if this threshold was not exceeded or the mean wind speed was $<0.6\text{ m s}^{-1}$. We followed the sign convention that positive CO₂ flux densities represent net efflux, and negative flux densities represent net uptake, of CO₂ by the ecosystem. We assessed the footprint climatology over the study period by calculating the footprint for each valid 30-min period using the model of Kljun et al. (2004) and then plotting contours of the average relative contributions of different land areas to the measured fluxes as in Rebmann et al. (2005) (see Fig. 1). We note that the measured fluxes did not originate only from within the area enclosed by the isopleths in Fig. 1. Rather, the isopleths represent the average relative contributions of different land areas over the 2-year period; however, individual 30-min flux footprints did intersect the road when winds were from that direction. This, combined with a relatively high source magnitude, meant that the traffic emissions contributed significantly to the measured fluxes, and this was especially apparent in winter when biological activity was low. Data are reported with respect to local standard time (UTC – 6 hr).

The overall data availability is shown by the grey shaded lines above the CO₂ flux fingerprint in Fig. 2. The longer data gaps were due to failures of the buried power system

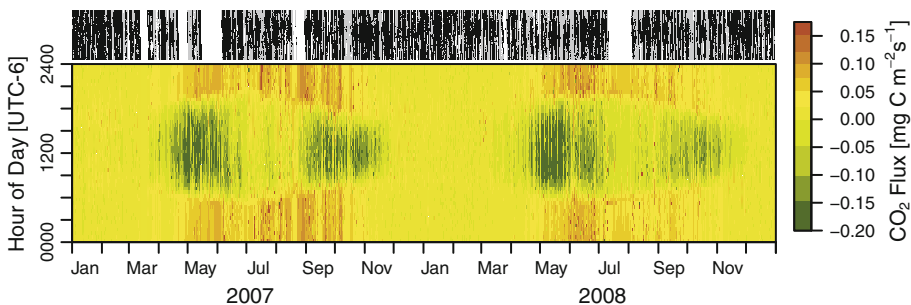


Fig. 2 Fingerprint of the CO₂ flux using gap-filled data for the years 2007 and 2008. Positive fluxes represent net efflux, whereas negative values represent net uptake, of CO₂ by the ecosystem. The *grey-shaded lines* above the flux fingerprint indicate data availability. *Black points* indicate high-quality data, *grey points* represent data removed due to low quality, and *white areas* indicate gaps due to instrument failure, tower maintenance, or power outages

during snow melt in spring or after lightning events in summer, and the shorter gaps were due to instrument maintenance and technical problems (13% in 2007 and 2008, white areas). Apart from the longer gaps, the overall data availability was reasonable, and only 23% of the measured fluxes (grey areas) were rejected due to our screening criteria, as described above.

2.4 Gap Filling

We used a gap-filling approach similar to that described by Falge et al. (2001). Daytime gaps ($PPFD > 10 \mu\text{mol m}^{-2} \text{s}^{-1}$) were filled using light-response curves (Ruimy et al. 1995) and nighttime gaps were filled using a temperature-driven model of ecosystem respiration (Lloyd and Taylor 1994). For the ecosystem respiration model, we implemented the parametrisation following Moureaux et al. (2006). The gap-filling process was performed iteratively, and the parameters for both models were determined using an overlapping, centred, running window that started with a length of seven days and increased by two days in each loop. The parameters were accepted only if at least 100 valid measurements were available in the window and the model parameters were significant (Student's t -test, $p < 0.1$) (Desai et al. 2005). We determined the start and end of the winter period when there was no plant uptake of CO_2 by examining the diurnal cycle of fluxes and additional meteorological data. During the winter period, the light-response model was not used and, thus, only the ecosystem respiration model was used for gap filling over the full diurnal cycle. The light-response model was again used immediately following spring snowmelt because the turf grass began to green up within one week after it was free of snow cover. Because the growing season of turf grasses normally ends abruptly following a hard frost, we added break points to the gap-filling routine to indicate sudden changes in ecosystem productivity. At these points, we forced the moving window to break and thus prevented the mixing of data from before and after the event. Additional break points were added to indicate the onset and end of the midsummer drought period. All break points were determined examining the diurnal cycle for significant, abrupt changes in CO_2 exchange, along with additional meteorological data.

Missing meteorological data were filled by linear regression using data from a National Weather Service cooperative station operated by the University of Minnesota that was located 750 m from our measurement site.

2.5 Traffic Counts and CO_2 Emission Factors

Traffic was counted continuously by the Ramsey County Department of Public Works using an inductive loop detector located at the nearest intersection along the road that passed our study site. We obtained counts of the number of vehicles that crossed the intersection in each direction of travel for every 15-min period. In order to assess the vehicle fleet composition, we recorded traffic using a web cam during a weekday in April 2008. Using the video recording, we manually counted traffic and assigned each vehicle to the following classes: motorcycles, passenger cars, pickup trucks and sport utility vehicles (SUVs), vans, buses, single-unit trucks, and trailer trucks.

We obtained CO_2 emission factors for each vehicle class from the Handbook Emission Factors for Road Transport (Version 2.1, INFRAS 2004). We retrieved emission factors that were appropriate for the fuel type distribution and vehicle age distribution typical of Minneapolis–Saint Paul suburban areas in 2007 (Adam Boies, pers. com. 2008), as well as the road characteristics (i.e., suburban, flat terrain, and 64 km h^{-1} (nominally 40 miles h^{-1}) speed limit). Then, we weighted the emission factors by the frequency of each vehicle class and

multiplied by the measured traffic counts to calculate the total CO₂ emissions from traffic for 30-min intervals matching our eddy-covariance measurements.

2.6 Estimating Traffic Effects on Measured CO₂ Fluxes—Development of an Empirical Model

We assessed the influence of traffic on the observed CO₂ fluxes by using a flux footprint model in combination with the continuous traffic count data. We used the parameterization (Kljun et al. 2004) of the footprint model from Kljun et al. (2002). In this model, the crosswind-integrated footprint prediction $\overline{f^y}$ represents the influence of the area located at a distance x from the tower and integrates the flux contribution over the entire width of the footprint. In order to assess the contribution of the road to the total CO₂ flux, we computed $\overline{f^y}$ for each 30-min measuring interval, setting x equal to the distance between the tower and the road along the direction of the mean wind (i.e., the upwind fetch). The boundary-layer height was defined at a constant value of 1000 m. As the traffic contribution decreases with increasing fetch, whilst the uncertainty of the footprint grows, we excluded from the empirical model any 30-min intervals when the fetch was >350 m (corresponding to wind directions between 190° and 350°, and the footprint being parallel to or pointing away from the road) and, instead, we set the estimated traffic CO₂ flux to zero.

In the following, the influence of the road within the footprint is denoted by $\overline{f^y}_{road}$. This term varied with turbulence and surface characteristics, depending on the following variables: the distance between the tower and the road in the prevailing wind direction, the friction velocity, the instrument height, the standard deviation of the vertical wind, and the roughness length. For a given wind direction (i.e., constant fetch), and instrument height, $\overline{f^y}_{road}$ varied with atmospheric stability and wind speed. In this case, a larger footprint corresponded to a greater influence from the road. On the other hand, for a given set of atmospheric conditions, $\overline{f^y}_{road}$ varied with wind direction since the fetch between the tower and the road varied with wind direction.

To estimate traffic CO₂ fluxes, we developed a multiple regression model that accounted for variations in both traffic and meteorological conditions, the latter through the information on the footprint and the fetch that was represented by $\overline{f^y}_{road}$. To exclude other environmental drivers, we fitted the model using winter data when the daily maximum soil temperature was below the freezing point and the snow cover was continuous. Under those conditions, there was no photosynthetic uptake by turf grass, and we could assume that the only ecosystem contribution to the measured CO₂ flux was a very low and nearly constant efflux due to soil respiration. During this period, the Pearson’s product-moment correlation (r) between the CO₂ flux and the traffic volume was 0.47, while the correlation between the CO₂ flux and $\overline{f^y}_{road}$ was 0.31. We fitted the following multiple regression model, including all interaction terms:

$$F_{CO_2, meas} = \underbrace{intercept + a\overline{f^y}_{road}}_{F_{CO_2, eco}} + \underbrace{bn_{vehicles} + c\overline{f^y}_{road}n_{vehicles}}_{F_{CO_2, traf}}, \tag{1}$$

where $F_{CO_2, meas}$ was the measured flux at the tower and $n_{vehicles}$ denoted the number of passing vehicles during the 30-min interval. The terms *intercept* and $a\overline{f^y}_{road}$ did not depend on $n_{vehicles}$ and, together, they represented the ecosystem CO₂ flux, $F_{CO_2, eco}$. The quantity $F_{CO_2, eco}$ is equivalent to the net ecosystem exchange (NEE) of CO₂ that is commonly reported for flux sites in natural ecosystems. The sum of the other two terms, $bn_{vehicles} + c\overline{f^y}_{road}n_{vehicles}$, provided an estimate of the traffic related flux, $F_{CO_2, traf}$.

3 Results and Discussion

3.1 CO₂ Flux Measurements

At first sight, the flux measurements over the turf-grass field did not appear to show signs that traffic emissions had contaminated the normal temporal patterns of ecosystem CO₂ fluxes. If traffic emissions were important, we would have expected to find positively biased fluxes during rush hours in the morning and early evening throughout the annual cycle. However, the flux fingerprint for the years 2007 and 2008 (Fig. 2) showed CO₂ fluxes that had generally similar diurnal, weekly, and annual patterns as compared to natural grasslands and pastures (Flanagan et al. 2002; Byrne et al. 2005). The annual cycle of CO₂ fluxes followed a similar pattern in both years. When soils were frozen and the ground was snow covered, the fluxes had small positive magnitudes and the ecosystem was a net source of CO₂. Following snowmelt in April, turf-grass photosynthesis began rapidly and the first negative fluxes were observed, increasing throughout the spring. This period of strong CO₂ uptake was followed by warmer and drier weather in mid-summer, and the flux fingerprint showed a mid-summer decline in growth rates that is characteristic of cool-season turf grasses (Fry and Huang 2004). In 2007, an unusually dry spring was followed by a warmer than average summer, and the flux fingerprint showed a more severe mid-summer decline in CO₂ uptake during that year. In both years, when cooler conditions returned in late summer and autumn, turf-grass growth increased and a second period net CO₂ uptake was observed in the flux fingerprint.

In addition to the flux fingerprint analyses, we examined the dataset in the following ways for evidence that traffic emissions had affected the measured CO₂ fluxes. First, we reasoned that CO₂ concentrations would be elevated when the wind direction was from the west, which represented the shortest distance between the tower and the road. However, we did not find a relationship between CO₂ concentration and wind direction. On the contrary, during the summer we found that CO₂ concentrations were commonly lower when the wind was from the west because this direction was also affected by strong plant uptake of CO₂ due to a golf course on the other side of the road. Second, if traffic emissions were important, we expected that light-response curves of the CO₂ flux would differ between weekday versus weekend periods. However, the scatter in the light-response curves was large relative to the magnitude of the traffic contribution, and thus no such pattern was found in the data. Third, we binned the data into periods when the wind direction was from the road versus other wind directions, and then compared light-response curves of the CO₂ flux. However, this comparison was confounded by the characteristically different weather conditions that occurred with the different wind sectors. Whereas north-westerly winds occurred with cooler weather, southerlies brought warm and humid air from the Gulf of Mexico. The systematic temperature differences that were associated with the wind patterns, and their consequent effects on ecosystem respiration, likely explain why we did not observe a signal of traffic emissions in these analyses.

3.2 Empirical Model of Traffic CO₂ Fluxes

A final set of analyses was limited to mid-winter periods when the soil was frozen to a depth of at least 0.05 m and the ground was covered by snow. During this period, there was no photosynthetic uptake by turf grass, and we can assume that the ecosystem contribution to the measured CO₂ flux was very low and varied within a narrow range depending on soil temperature. Despite this, the variations in the measured winter fluxes were only weakly correlated with soil temperature ($r = 0.05$). Instead, we found that the measured CO₂ fluxes

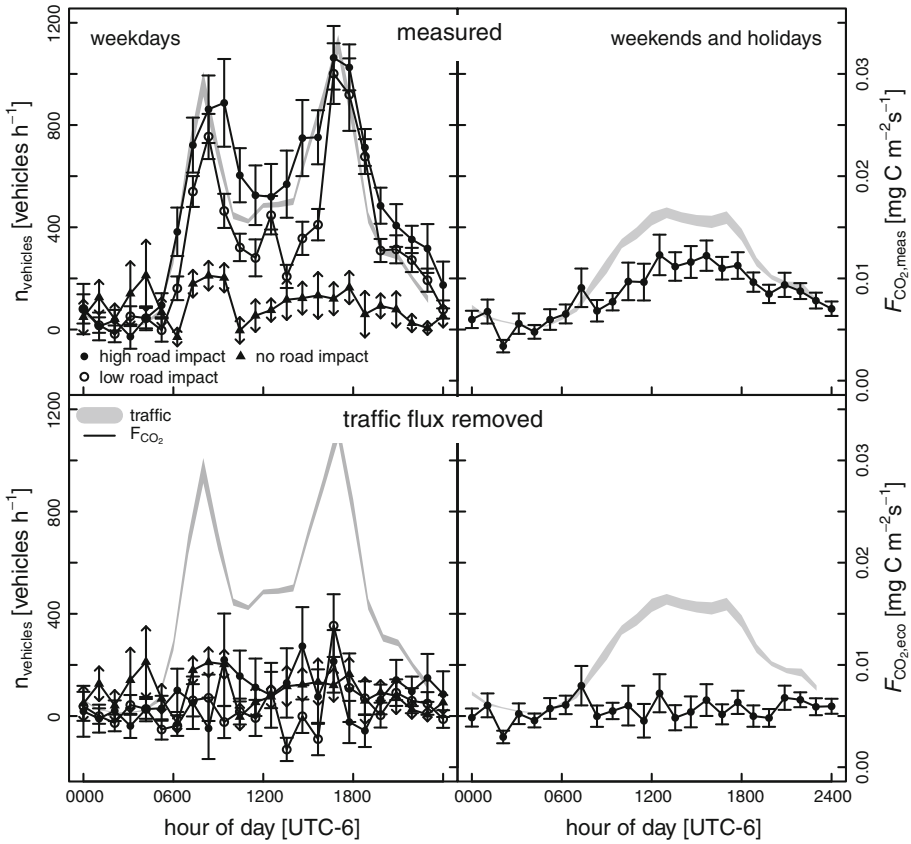


Fig. 3 Diurnal cycle of the traffic volume and the CO₂ flux for weekdays (*left panels*) and for weekends and holidays (*right panels*) binned into 1-hr classes. The selected data were from all winter days in 2007 and 2008 when the soil was frozen to a depth of at least 0.05 m and there was a continuous snow cover. The *grey band* shows the 95% confidence interval for the traffic volume. The CO₂ fluxes are means for each 1-hr class and the corresponding *error bars* indicate ± 1 standard error. For the weekdays, the fluxes were split into three classes, one with high road impact ($\overline{f^y_{road}} > 0.001$, *round symbols and lined error bars*), one with low road impact ($0.001 > \overline{f^y_{road}} > 0.00005$, *open symbols and lined error bars*), and no traffic impact ($\overline{f^y_{road}} = 0$ and wind direction $< 180^\circ$, *triangle symbols and arrow error bars*)

were strongly related to the number of vehicles passing on the nearby road (upper panels in Fig. 3). The correlation between the measured CO₂ flux and the traffic counts was 0.46 on weekdays and 0.27 on weekends. With this information, we fitted the model described in Sect. 2.6 to separate traffic CO₂ emissions from the ecosystem CO₂ flux.

We fitted Eq. 1, including all interaction terms, and obtained a parametrisation with $r^2 = 0.35$ (Table 1). That the model explained only 35% of the variation in the measured CO₂ flux was not unexpected given that ecosystem fluxes (i.e., soil respiration driven by temperature) also contributed to the measured CO₂ fluxes, even in winter. In addition, the footprint climatology (Fig. 1) showed that the relative influence of locations as far away from the tower as the road would have been small for the entire years 2007 and 2008. However, despite the fact that the main source area of the measured fluxes was located within the turf-grass field, the source strength of motor vehicle emissions was large and there was a clear signal of traffic in the CO₂ flux when the wind direction was from the road towards the tower (upper panels in Fig. 3). In order to remove the traffic CO₂ emissions from our measurements,

Table 1 Parameterisation of the empirical model presented in Eq. 1

		Estimate	Std. Estimate	<i>p</i> -value	<i>r</i> ²
<i>Intercept</i>		5.6×10^{-3}	4.4×10^{-4}	<0.001	
<i>a</i>	$\left[\frac{\text{mg C}}{\text{m}^2 \text{ s}} \right]$	0.12	0.23	0.61	
<i>b</i>	$\left[\frac{\text{mg C}}{\text{m}^2 \text{ s vehicle}} \right]$	3.2×10^{-5}	1.7×10^{-6}	< 0.001	
<i>c</i>	$\left[\frac{\text{mg C}}{\text{m s vehicle}} \right]$	5.8×10^{-3}	8.7×10^{-4}	< 0.001	0.35

The parameters in boldface were used to calculate the traffic-related flux $F_{\text{CO}_2, \text{traf}}$

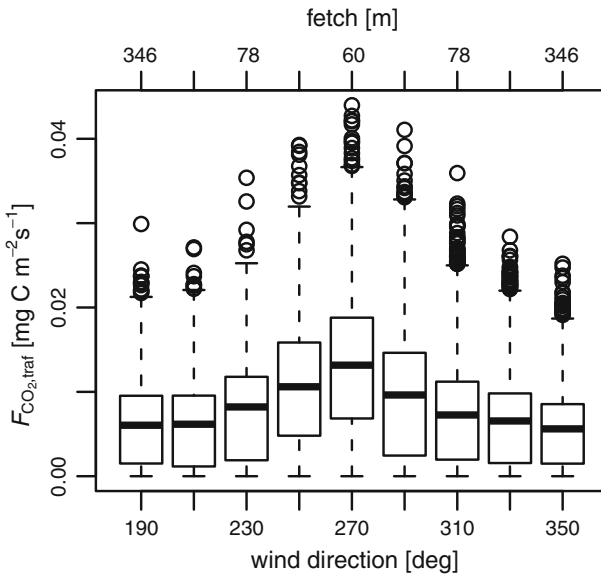


Fig. 4 Traffic-related flux $F_{\text{CO}_2, \text{traf}}$ variation with the fetch, i.e. the distance *x* from the tower to the road (upper horizontal axis), which in turn varied with the prevailing wind direction (lower horizontal axis). Boxes show the quartiles and horizontal bars indicate the median for each wind direction class. Whiskers show the lesser of the full data range or ± 1.5 times the inter-quartile range and open circles indicate data points >1.5 times the inter-quartile range. Within each box, the calculated CO₂ contribution per vehicle ($F_{\text{CO}_2, \text{traf}}/n_{\text{vehicles}}$) is linearly dependent on the footprint size ($\overline{f^y}_{\text{road}}$)

we subtracted the estimated traffic-related flux $F_{\text{CO}_2, \text{traf}}$ (i.e., boldface parameters in Table 1). After subtracting $F_{\text{CO}_2, \text{traf}}$ using this approach, there was no longer a diurnal cycle in the observed fluxes, which was the pattern we would have expected for a field that was covered with snow (lower panels in Fig. 3).

Figure 4 illustrates the characteristics of our empirical model of traffic CO₂ fluxes. Plotting the estimated $F_{\text{CO}_2, \text{traf}}$ by the wind direction resulted in a bell-shaped curve. The wind direction is directly related to the fetch over the turf-grass field, and the highest fluxes from traffic occurred when winds came directly from the road to the tower and the fetch was shortest. The scatter within each wind sector may be attributed to both variations in the dimensions of the footprint with atmospheric conditions and variations in traffic counts with time. Variations in roughness length with season or wind direction were accounted for in the empirical model,

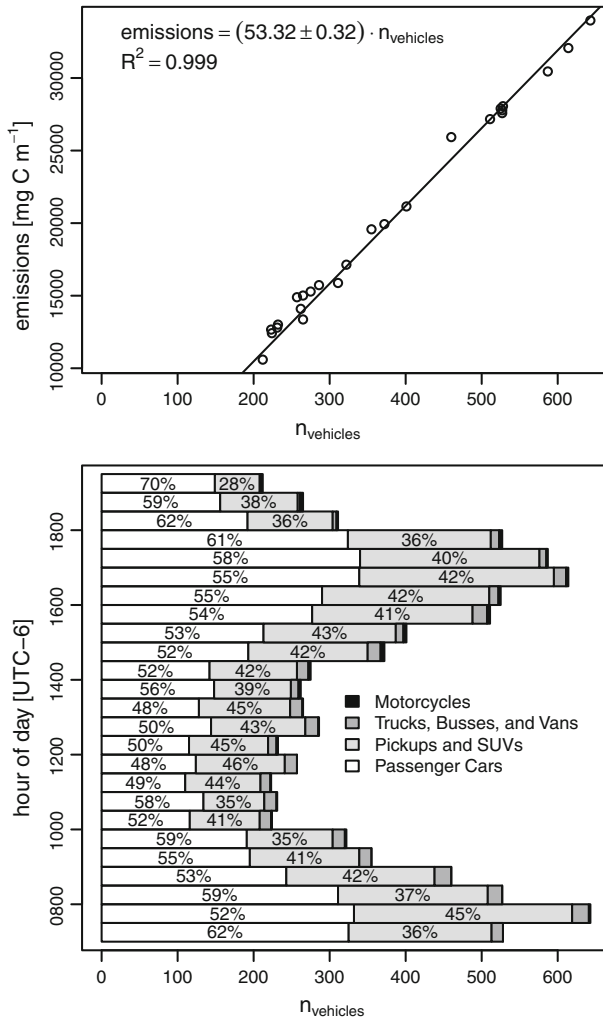


Fig. 5 Upper panel relationship between the modelled CO₂ emissions from traffic and the number of passing vehicles. Lower panel half-hourly traffic composition based on manual counts. The numbers in the bars show the proportion of each bar

because this was based on the footprint information, and measured values of z_0 were used to compute the footprint for each 30-min period.

3.3 Empirical Model Compared to Traffic CO₂ Flux Estimates Based on Emission Factors

As a check on the magnitude of $F_{\text{CO}_2, \text{traf}}$ predicted by our empirical model, we used published emission factors to independently estimate the amount of CO₂ released by passing traffic. First, we assessed whether there was a linear relationship between the CO₂ emissions by traffic, as estimated in Sect. 2.5, and the number of passing vehicles (Fig. 5). A linear relationship between the number of passing vehicles and the observed flux would be expected if the fleet composition did not vary significantly over time. This relationship yielded $r^2 = 0.999$ and

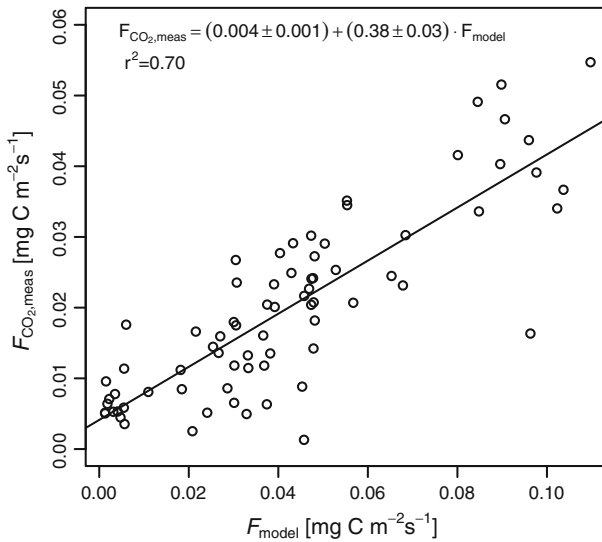


Fig. 6 Measured CO_2 flux compared to modelled CO_2 emissions by vehicles, scaled by the crosswind-integrated footprint for the distance of the road. The *line* shows the linear model between the plotted variables. The intercept of the linear regression can be interpreted as the biogenic wintertime flux

the variations in fleet composition over the course of the day were minor (lower panel in Fig. 5); therefore, we determined that a linear relationship was appropriate for our site.

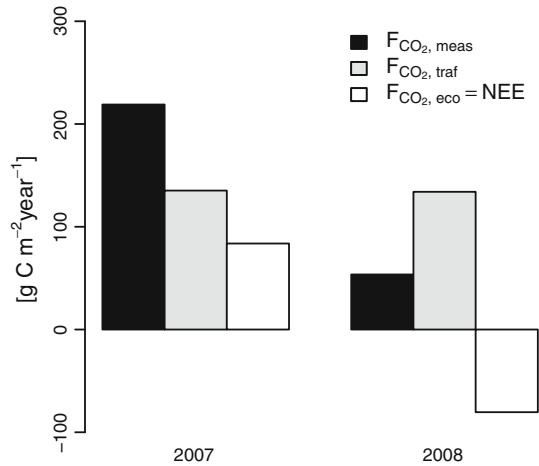
For the following analysis we used the same winter dataset that was used to force the model, but we included only data with wind directions from $240\text{--}300^\circ$, so that traffic contributions would be at their maximum. For the same reason, we also excluded data when more than 90% of the footprint was within the turf-grass area and did not overlap the road. These restrictions reduced the dataset to 74 valid 30-min records. The linear relationship between $F_{\text{CO}_2,\text{traf}}$ and the number of passing vehicles yielded an average of $53.32 \text{ mg C m}^{-1} \text{ vehicle}^{-1}$ (upper panel in Fig. 5). We multiplied this emission factor by the number of passing vehicles to produce an estimate of the traffic-related CO_2 emissions for each 30-min flux measurement interval. In order to compare this estimated traffic related flux to that obtained from the eddy-covariance system, we multiplied the traffic-related emission rate with $\overline{f}^y_{\text{road}}$ to account for the size of the footprint at that time period and divided it by 1800 to obtain an emission rate per second instead of per 30-min.

Figure 6 shows a scatterplot of $F_{\text{CO}_2,\text{meas}}$ against the CO_2 fluxes that were estimated using emission factors, as well as the linear regression between these variables. The intercept of $0.004 \text{ mg C m}^{-2} \text{ s}^{-1}$ is similar to the residual flux after applying the empirical traffic correction model (see Fig. 3) and can be attributed to the average winter soil respiration. At the same time, we note that the empirical traffic correction model described in Sect. 2.6 has the advantages that potential biases in estimating per-vehicle traffic emissions are not translated into the traffic correction and we do not need the footprint width.

3.4 Impact of Traffic Emissions on Annual CO_2 Fluxes at this Site

We assessed the overall influence of the traffic-related CO_2 flux on an annual basis by running the gap-filling procedure described in Sect. 2.4, once using a dataset in which the influence of traffic was removed and once where it was not. Removing the CO_2 flux caused by

Fig. 7 Annual CO₂ budget separated into $F_{\text{CO}_2, \text{meas}}$ (black), $F_{\text{CO}_2, \text{traf}}$ (grey) and the difference between these two fluxes, $F_{\text{CO}_2, \text{eco}}$ (white)



traffic changed the annual carbon budget by 135 g C m^{-2} in 2007 and by 134 g C m^{-2} in 2008 (see Fig. 7). We note that these values do not represent an exact quantification of the CO₂ flux contribution from traffic. This is because our gap-filling procedure, as with most such approaches, did not account for differences in CO₂ flux with wind direction. This means that, when we ran the gap-filling procedure without first having removed traffic effects from the data, gross primary productivity could have been underestimated and ecosystem respiration overestimated on either side of the gap, thereby propagating effects of a given traffic flux into gap-filled values. After subtracting $F_{\text{CO}_2, \text{traf}}$, the pattern of $F_{\text{CO}_2, \text{eco}}$ between the two years showed the effect of observed weather conditions: the dry period in spring 2007 reduced photosynthetic uptake, leading to a higher annual NEE, while the relatively long and cold winter of 2008 reduced winter respiration, leading to a lower annual NEE. The similar magnitude of the traffic effect between 2007 and 2008 is consistent with the similar amounts of traffic in the two years (total volume of 3.51×10^6 vehicles in 2007 and 3.40×10^6 vehicles in 2008). In addition, it suggests that variations of the flux footprint over time are similar between the two years on average. The fact that traffic-related CO₂ fluxes are essentially equal in 2007 and 2008 means that the relative differences in NEE between years are robust. Even though the road was outside of the main footprint area and the effect of traffic emissions on each 30-min flux observation was small, these values show that traffic had a significant impact on the annual carbon budget because it represented a small, continuous positive bias. For our study site, the correction converted the ecosystem from a net source to a net sink in 2008.

4 Conclusions

We measured CO₂ fluxes above a lawn that was relatively large for a patch of homogeneous turf-grass cover in a suburban neighbourhood. We found that, even with a low measurement height of 1.35 m, the limited fetch (from 60 to a few hundred metres) was insufficient to completely exclude fluxes from adjacent areas. These results are consistent with the established rule for micrometeorological measurements that the uniform fetch should equal at least 100 times the measurement height (Horst and Weil 1994). However, we also found that a footprint model could successfully quantify the effects of traffic emissions from outside the measurement area, given that the location of the road relative to the flux tower was known and the CO₂

source from traffic could be estimated using traffic counts. Our empirical model of traffic CO₂ fluxes agreed closely with a bottom-up approach that used footprint-weighted emission factors. This further suggests that the footprint model produced reasonable estimates even at the edge of its domain. While we believe the empirical model accurately quantified the main effects of traffic emissions on the measured fluxes, we recommend nonetheless that the corrected, ecosystem CO₂ flux data be interpreted with caution. The approach we developed may be useful for other sites as investigators seek to make eddy-covariance measurements on small patches within heterogeneous landscapes where there are significant contrasts in flux rates. However, we caution that the modelling approach is empirical and will need to be adapted individually to each site.

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