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Toward understanding the behavior of carbon dioxide and surface energy fluxes in the urbanized semi-arid Salt Lake Valley, Utah, USA

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ABSTRACT

This paper describes the Salt Lake Valley urban flux study that was designed to understand the role of vegetation and urbanization on CO_2 and surface energy fluxes over surfaces typical of urbanized and pre-urbanized land cover in the semi-arid Salt Lake Valley. The eddy covariance technique was applied at two different sites with distinct land forms within an urbanizing mountain basin. One site was located in a suburban neighborhood with substantial mature vegetative cover (urban forest), prototypical of many residential neighborhoods in the valley, and the other site was in a pre-urban area. Results indicate that the suburban site was a net sink of CO_2 during the midday period in the summer due to photosynthetic activity and was a source of CO_2 during the evening and nighttime periods. The pre-urban site was a net source of CO_2 with positive fluxes throughout the day. Even though the vegetation at the suburban site sequestered carbon dioxide during the daytime in the summer months, the daily net CO_2 flux remained positive (i.e. a net source). In addition, the net CO_2 emission at the suburban site was found to be three times greater in the fall than during summer. The vegetative cover around the suburban site also had a significant impact on the partitioning of the surface energy fluxes. During the summer months, the contribution of the latent heat flux was substantially higher at the suburban site, while the sensible heat flux was much larger at the pre-urban site. The general behavior of the energy and CO_2 fluxes are consistent with typical climate modification due to urbanization in semi-arid climates (i.e. introduction of an urban forest), but quite different from changes reported in more mesic climates where highly vegetated regions are replaced with urban surfaces.

1. Introduction

A large database and general understanding of CO_2 fluxes exist for natural forests and non-urbanized land covers. In fact, Baldocchi et al. (2001) reported that over 180 sites were monitoring, nearly continuously, ecosystem carbon dioxide and water vapor exchange worldwide. This has led to substantially improved understanding of trace-gas fluxes in non-urban ecosystems, however there is still a substantial gap in urban areas. Urban CO_2 flux studies conducted in various cities around the world have begun to quantify net CO_2 emissions and the factors that affect CO_2 fluxes in urban areas. Vegetative cover, climate and human activity (e.g. automobile gasoline combustion and natural gas combustion) have been found to significantly influence CO_2 fluxes in urban areas (Pataki et al., 2006).

The Salt Lake Valley (SLV) urban flux study was devised as part of the Urban Trace-gas Emission Study (UTES) (Pataki et al., 2009) to quantify net urban CO_2 emissions and to address the following questions: *How does the urban forest impact the CO_2 and energy budgets in semi-arid regions? How do these fluxes vary diurnally and seasonally? What are the dominant factors that contribute to CO_2 emissions in an urban area?, and Can these emissions be quantified and related to the net CO_2 flux?* While this paper does not answer all of these questions, it provides insight into aspects of each of these question. A great deal of work is still needed to answer the questions and fully explain the underlying biophysical processes.

Many of the basic concepts underlying urban CO_2 fluxes were introduced by Grimmond et al. (2002) during the Chicago flux experiment which was the first urban CO_2 flux study conducted in the U.S. Additional urban CO_2 flux studies have been conducted in North America, Europe and Asia since that time (see Table 1). The Chicago study found that the urban site acted as a net source of CO_2 at all time periods during the summer, even though 39% of the area within the flux footprint of the tower was covered by vegetation. The vegetation did reduce the daytime emissions, but did not offset

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Table 1
Summary of previous urban CO_2 flux studies (Note that in Melbourne there were two measurement sites).

City	Duration	Land cover	CO_2 fluxes $\mu mol\ m^{-2}\ s^{-1}$	CO_2 conc. ppm
Chicago (Grimmond et al., 2002)	June 1995– August 1995	36% Buildings 25% Impervious 39%Vegetation	Summer 0.5–11.4	Summer 370–410
Tokyo (Moriwaki and Kanda, 2004)	May 2001– Apr 2002	33% Buildings 21% Vegetation 38% Impervious 8% Pervious	Summer 4.5–11.4 Winter 4.5–25	Summer 350–390 Winter 370–430
Basel (Vogt et al., 2006)	Summer 02	54% Buildings 16% Vegetation	Summer 1–20	Summer 362–423
Copenhagen (Soegaard and Moeller-Jensen, 2003)	Jan 2001– Dec 2001	47% Vegetation		
Edinburgh (Nemitz et al., 2002)	Oct 2000– Nov 2000	20% Vegetation	Winter −12 to 135	Winter 364–416
Marseille (Grimmond et al., 2004)	Jun 2001– Jul 2001	14% Vegetation	Summer 1–37	
Mexico City (Velasco et al., 2005)	Apr 2003–	17% Vegetation	Summer 2.3–19.3	Summer 372–432
Melbourne (Coutts et al., 2007)			++ Summer	++ Summer
		++	2–8	362–372
	++Feb 2004 -Jun2005	15% Pervious 23% Vegetation	Winter 3.5–11	Winter 370–377
	**Feb 2004- Jul 2004	** 20% Pervious 27% Vegetation	** Summer 2–14 Winter 1.8–17.6	** Summer 357–372 Winter 359–374

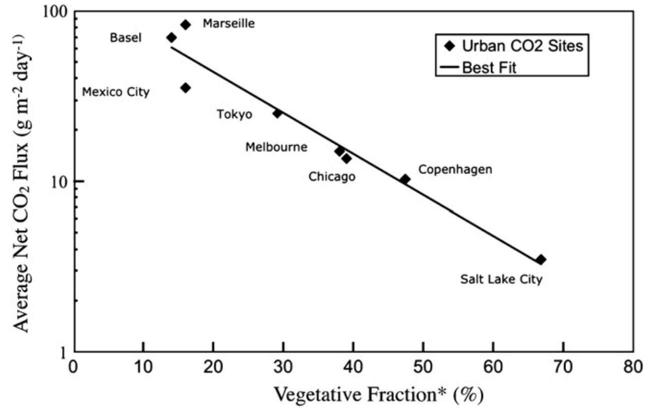

Fig. 1. Variation of the average daily net CO_2 flux for different cities around the world during the summer months as a function of vegetative land cover. The curve is an exponential function of the form $y = Ae^{-b}$, where $A = 132$ $gm^{-2}\ day^{-1}$and $b = 0.055$ with an $R^2 \sim 0.95$. *Note that the vegetative land cover includes fraction of vegetation plus pervious surfaces as reported by the individual studies (see Table 1). Studies not sufficiently reporting land cover and those not reporting summertime fluxes have been omitted.

the anthropogenic emissions. The experiment also focused on addressing problems related to measuring CO_2 fluxes in urban areas, especially with issues related to characterizing urban land form, tower footprint and atmospheric stability. The work showed that there was a need for long term flux studies in urban areas.

Urban CO_2 fluxes are dominated by a number of factors including land cover, land use and climate. Among these, land cover appears to be particularly important. Suburban sites typically have smaller, yet usually net positive fluxes, owing to increased vegetation. This variability can be illustrated by considering summertime CO_2 fluxes. At the Chicago site, net CO_2 fluxes ranged between 8 and 16 $\mu mol\ m^{-2}\ s^{-1}$. Summertime fluxes measured in Melbourne, Australia (Coutts et al., 2007), varied between 2 and 14 $\mu mol\ m^{-2}\ s^{-1}$, while in Tokyo (Moriwaki and Kanda, 2004), the CO_2 fluxes varied between 4.5 and 11.4 $\mu mol\ m^{-2}\ s^{-1}$. CO_2 fluxes measured in suburban locations in other cities around the world have shown similar trends. In Basel, Switzerland, CO_2 fluxes were measured closer to the city center (Rotach et al., 2005). Fluxes as high as 30 $\mu mol\ m^{-2}\ s^{-1}$ (Vogt et al., 2006) were observed. Similarly, Marseille, France (Grimmond et al., 2004) showed very high fluxes in the highly urbanized downtown area.

Fig. 1 shows the variation of averaged daily net CO_2 flux as a function of vegetative cover for various cities around the world during summertime. The results clearly indicate a strong negative correlation between CO_2 flux and vegetative surface cover in urban areas. In fact, the R^2 of the best fit line for the cities shown is over 0.95. This is particularly surprising given the substantial variation in climate, types of vegetation and underlying urban processes (i.e. anthropogenic sources). While Grimmond and Oke (2002) have shown that energy fluxes appear to scale well with vegetative fraction, there is much more variability in those data. We hypothesize that this high correlation may be a result of a dominance of mid-latitude cities in the sampled studies, combined with how cities are typically laid out and constructed. As vegetative fraction increases, there is less space available for anthropogenic activities. In addition, humans tend to separate manufacturing activities from their residence. Here, it is important to note that the vegetative fraction shown, combines the typically reported vegetative fraction with pervious surfaces. This was done as a result of the variability in the reporting of vegetative fraction for different studies and indicates a need for a consistent method of reporting land cover information.

In addition to land cover characteristics, CO_2 fluxes are also sensitive to seasonal variations. In Edinburgh, Scotland (Nemitz et al., 2002), wintertime CO_2 fluxes were as high as 75 $\mu mol\ m^{-2}\ s^{-1}$. Similarly, in Tokyo the wintertime flux peaks were twice that of the summertime. Combustion of natural gas, used for commercial and residential heating purposes, contributed heavily. Nemitz et al. (2002) found that nearly 65% of the net CO_2 in Edinburgh was from natural gas combustion during the winter months.

Anthropogenic emissions such as traffic are also an important source of CO_2 in cities and have a significant impact on the diurnal pattern of CO_2 fluxes. A study in Copenhagen (Soegaard and Moeller-Jensen, 2003) found a high correlation between CO_2 fluxes and traffic flow. The flux studies conducted in Basel, Switzerland (Vogt et al., 2006), Rome (Gratani and Varone, 2005) and Edinburgh, UK (Nemitz et al., 2002) also found high correlations between CO_2 fluxes and traffic flow. In Basel, CO_2 measurements were also made within the roughness sub-layer in a highly urbanized area. High variability in CO_2 concentrations was observed close to the ground level due to traffic. Data from Mexico City (Velasco et al., 2005) and Melbourne, Australia (Coutts et al., 2007) also show the impact of traffic flow on CO_2 fluxes. In Chicago and Melbourne peak flux values were observed during the morning and evening rush hour traffic.

In addition to flux experiments, researchers have attempted to quantify the contributions of various urban sources of CO_2 through isotopic analysis (Lichtfouse et al., 2002; Widory and Javoy, 2003; Zimnoch et al., 2004). Pataki et al. (2003) used isotopic analysis to identify principal sources of CO_2 in Salt Lake City, USA. The year long study found a high correlation between energy usage and CO_2 concentration. Natural gas combustion was a major contributor during the winter months and tree respiration had a significant impact during the growing season. The study also found that the

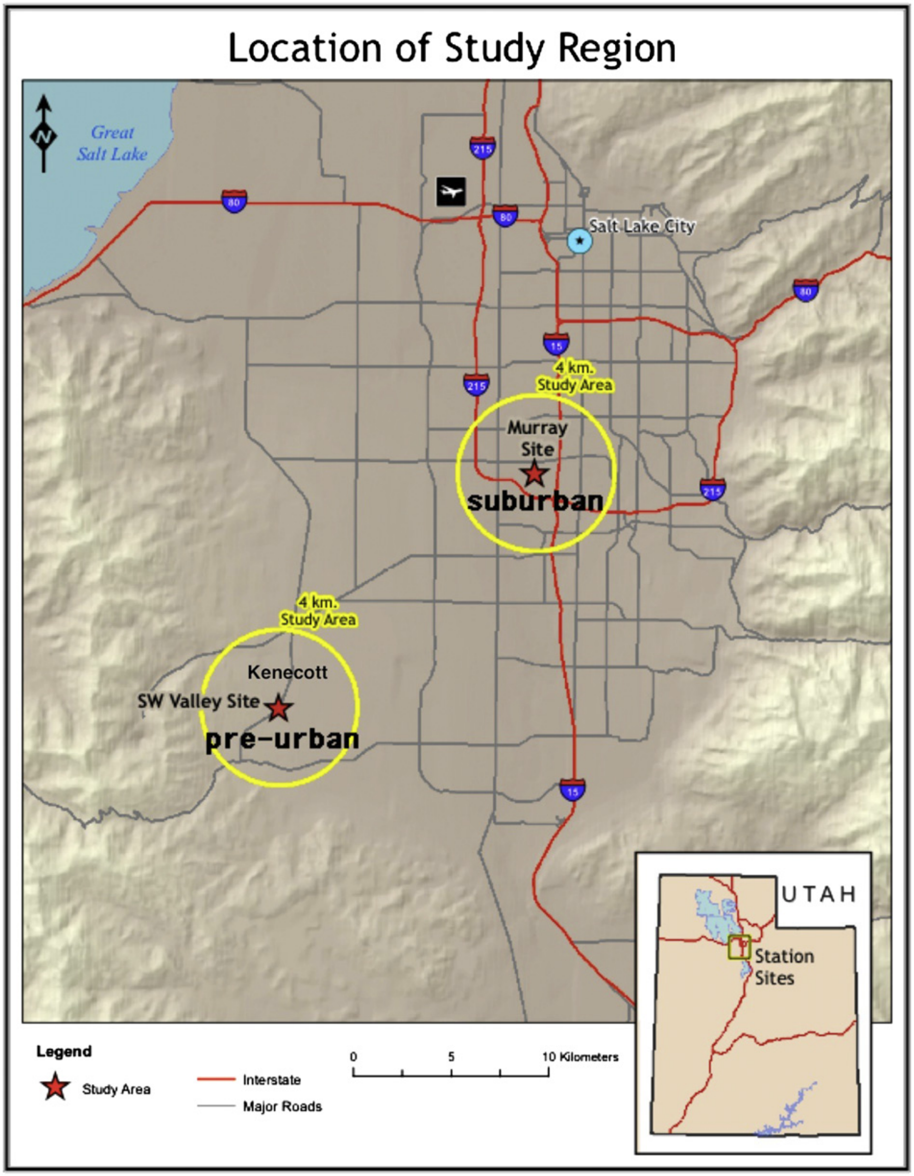

Fig. 2. Map indicating both measurement sites located within Salt Lake Valley. Data for the map were obtained from Utah GIS Portal (2007).

contribution from gasoline combustion remained steady all through the year.

The SLV study is unique as it is the first time CO_2 fluxes have been measured in a semi-arid desert city. In the following sections, flux measurements that were made at two locations with unique urban land forms within the same valley, in order to understand the impact of urbanization on CO_2 and surface energy fluxes, will be discussed in detail. One of the primary goals of this project has been to maintain a continuous database for CO_2 and energy fluxes for the valley and to understand how future urban growth will affect energy usage and its impact on the microclimate.

2. Observation sites

The Salt Lake Valley is located in an intermountain basin situated in the western part of the United States. The metropolitan area is located south-east of the Great Salt Lake, with the Wasatch and Oquirrh Mountain Ranges on its eastern and western borders (See Fig. 2). The valley is ~1320 m above sea level and experiences semi-arid climatic conditions (Quattrochi and Ridd, 1998). Within the valley, experiments were performed at two sites with substantially different land forms; a suburban residential area (*Murray Site*, 40.648061° N, 111.916231° W), located near the center of the Salt Lake Valley, and a pre-urban site (*Kennecott*, 40.38416° N, 112.069625° W) which resembled what much of the west side of the Salt Lake Valley looked like before it was developed. During the summer months when the experiment was conducted, the weather was typically warm and dry. During the 2005 and 2007 field campaigns, the climate was slightly warmer and drier than the 30 year average for the months of June–September. In 2005 and 2007 respectively, the temperatures were 2.5 and 0.5 °C warmer than average, while the rainfall was 2.6 and 5.1 mm below average (NWS, 2010).

The suburban site, Murray, is mostly residential and is ~1306 m above sea level. The urban form around this site is similar to many other residential neighborhoods in the valley. As shown in Fig. 2, the site is centrally located within the valley. There are freeways (I-15 and I-215) 1–2 km east and south of the site respectively.

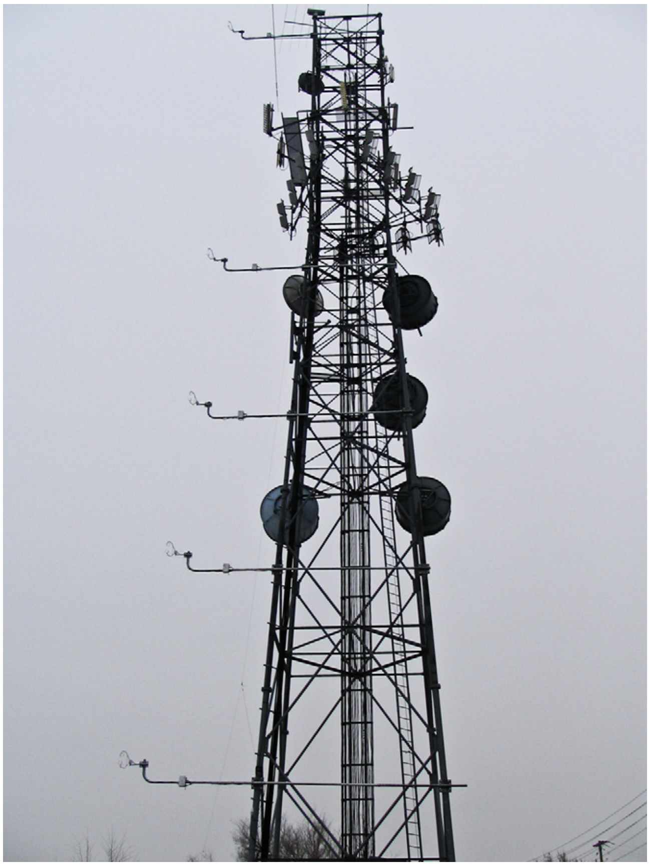

Fig. 3. Measurement tower at Murray (suburban) study site.

Fig. 3 shows the measurement tower at the suburban site and Fig. 4 illustrates the urban characteristics around the Murray flux tower. In a 2 km × 2 km region around the tower ∼67% of the area is covered by vegetation. The plan area fraction of buildings is 17% and the Leaf Area Index (LAI) for the month of July in 2005 was 3.6 (see Table 2 and Fig. 4 for detailed values). The LAI measured only includes trees. The LAI was estimated using a LI-COR LAI-2000 (Lincoln, NE, USA) plant canopy analyzer (Bush, 2010 personal communication). A single LAI-2000 instrument was used to measure both above canopy and within canopy with a 45° view cap. The sensor was placed next to the bole of each tree, below the crown, such that the view cap blocked both the scientist making the measurement and the tree bole from the sensor field of view. For each tree, one above canopy reading and five below canopy readings (taken at different locations around the bole) were made. The LAI-2000 uses five different angles in the standard LAI calculations (LI-COR, 1992), but because the present measurements were on isolated trees, and in order to avoid including angles that may be 'seeing' sky instead of canopy, the data were further processed using the LI-COR's FV2000 software to mask several of the sensor viewing angles. All angles except the two most zenith angles (7° and 23°) were masked to ensure that tree canopy was being 'viewed' in all cases. This masking method may have resulted in larger estimates of LAI overall, but was done to treat all canopies the same regardless of crown width and to remove all potential sky readings from influencing the computed LAI values.

Fig. 5 shows the tree and building height distribution around the suburban site. The average building height around the site was 4.4 m (height from ground to the top most part of the roof was considered to represent the building height) and most of buildings were two-storied residential houses. The trees were deciduous and evergreen and most of them are non-native and manually planted. The dominant tree types were: pines (23%), fruit (20.6%), Aspen (13%) and Maples (10%). Fig. 6 shows the 100 homes (shaded blocks) that were chosen in the suburban neighborhood where tree and building heights were measured manually.

The pre-urban site, Kenecott, is located in the south-western part of the valley (see Fig. 2), close to the Oquirrh mountain range. The site is located on gently sloping terrain. The site is called pre-urban because it is presently non-urbanized, but in close proximity (3–5 km) to urbanized land cover. Based on present development plans, this area is likely to be transformed (urbanized) in the near future. Currently, the area surrounding the Kenecott tower is covered with non-native sage, grasses and agricultural land. Most of the sage bushes around the site were <2 m tall (see Fig. 7). Situated at ∼1576 m above sea level, the Kenecott site is ∼270 m higher than the Murray site.

3. Instrumentation

3.1. Instrumentation at suburban site – Murray

During the summer 2005 flux experiment, a 37 m tall communication tower, equipped with five Campbell Scientific CSAT3 sonic anemometers (mounted at 5.9, 12.1, 17.1, 23.5 and 35.9 m above ground) was used to make observations at the Murray site. Carbon dioxide and water vapor concentrations were measured using a LI-COR 7000 closed path gas analyzer. Air was drawn through a 40 m long tube, 0.0127 m internal diameter with a pump (KNF UNMP830, flow rate – 3.1 lpm) from the top of the tower to the LI-COR 7000. The LI-COR 7000 was housed in a temperature controlled room at the bottom of the tower. The Murray tower was also equipped with a Campbell Scientific NL100 network interface for internet connectivity.

For the 2007 flux experiment, the Murray suburban site was equipped with a single CSAT3 sonic anemometer at 35.9 m and a LI-COR 7000 to monitor CO_2 and water vapor concentrations. The gas analyzer was set up to run in differential mode with continuous zero-gas flowing through the reference cell. The suburban site was also equipped with a Kipp & Zonen CNR1 net radiation meter (36.5 m above ground) along with Campbell Scientific HFP01-L & TCAV-L soil heat flux sensors to measure the ground heat flux. Two heat flux sensors, 1 m apart were used. Both heat flux sensors were buried 10 cm from the ground level. Tables 3 and 4 show all the instrumentation used during the 2005 and 2007 experiments.

3.2. Instrumentation at pre-urban site – Kenecott

The pre-urban site, Kenecott, consisted of a 7 m tall aluminum tower mounted on an elevated (∼2.5 m) platform that carried three Campbell Scientific CSAT3 sonic anemometers (5, 7, 9 m above ground). A LI-COR 6260 infrared gas analyzer was used to measure carbon dioxide and water vapor concentrations. The gas analyzer was set up to run in differential mode with continuous zero-gas flowing through the reference cell. Kipp & Zonen CNR1 net radiation meter and Campbell Scientific HFP01-L & TCAV-L soil heat flux sensors were also used at the pre-urban site. Two heat flux sensors, 1 m apart were used. Both sensors were buried 10 cm from the ground level. The site used a Campbell Scientific CR5000 datalogger. The pre-urban site, was not in operation for the 2007 experiment.

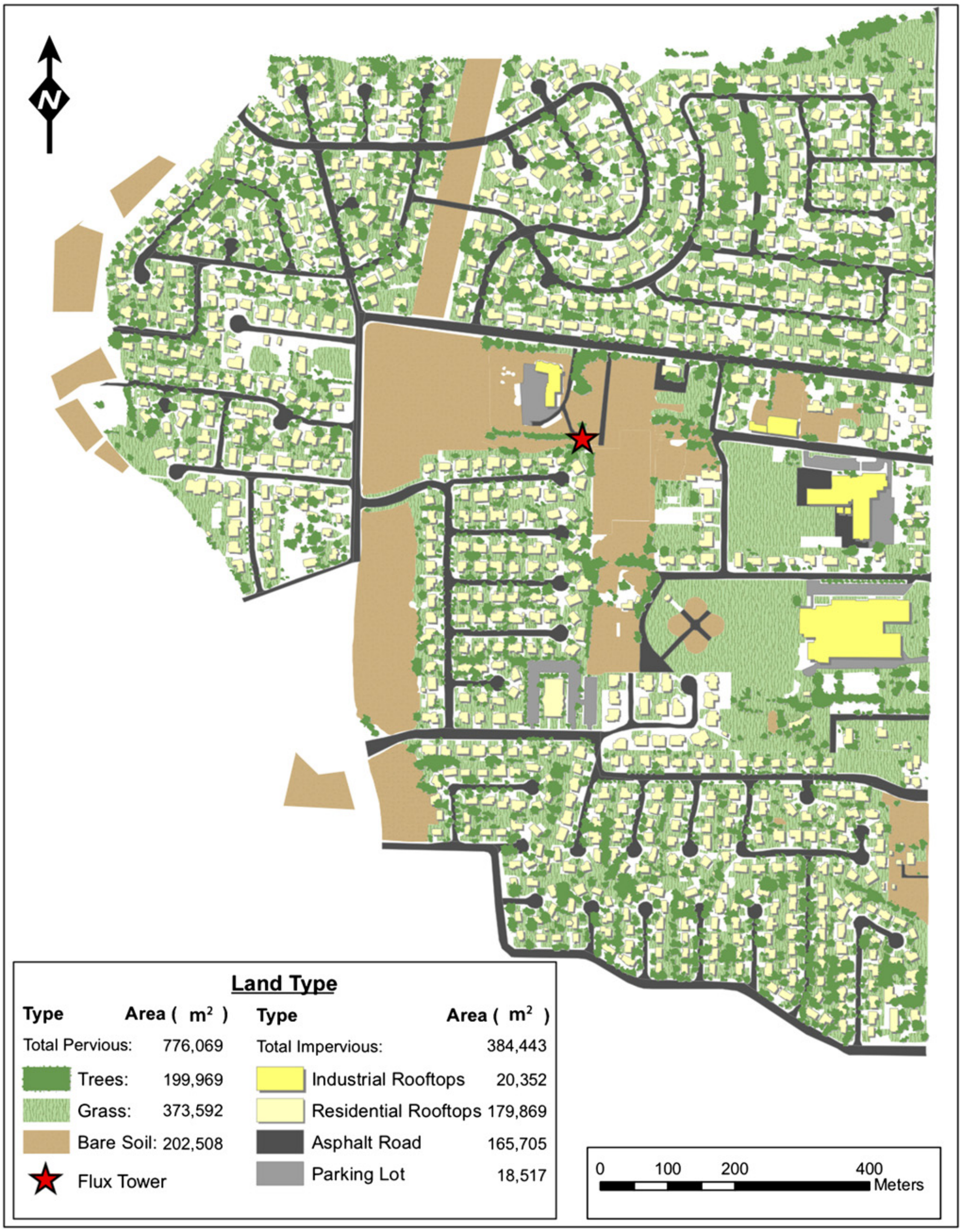

Fig. 4. Detailed survey of the land type distribution around the highly vegetated Murray (suburban) study site.

4. Data processing

Data presented in this paper were obtained during summer 2005 and fall 2007 field campaigns. In summer 2005, CO_2, latent and sensible heat fluxes were measured from June to September at both sites. The flux experiment was restarted at the suburban site in September 2007. Fluxes were not monitored during the winter.

At both sites, for the entire field campaign, velocity, temperature, CO_2 concentration and H_2O concentration data were sampled at 10 Hz. For calculating turbulence statistics, the raw dataset was linearly detrended using 5-min windows. The detrended signal was then used to calculate half hour averages of CO_2 and surface energy fluxes. Finally, the data were binned together to obtain ensemble monthly averages.

The Wilzack et al. (2001) coordinate rotation technique was applied to accommodate for errors related to topography. A lag correction technique was employed (Fan et al., 1990) to account for the delay between the velocity and carbon dioxide measurements recorded by LI-COR'S (LI-COR 7000 & LI-COR 6260) closed path gas analyzers. At the suburban site, the lag was approximately 22 s and at the pre-urban site, the lag was close to 4 s.

Table 2
Urban morphology characteristics of the Murray suburban site.

Average building height	4.4 m
Average tree height	6.5 m
Plan area fraction covered by vegetated surfaces (trees and grass)	49%
Plan area fraction covered by other pervious surfaces (bare soil)	18%
Plan area fraction covered by roof top	17%
Plan area fraction covered by roads and parking lot	16%
Leaf area index	3.6

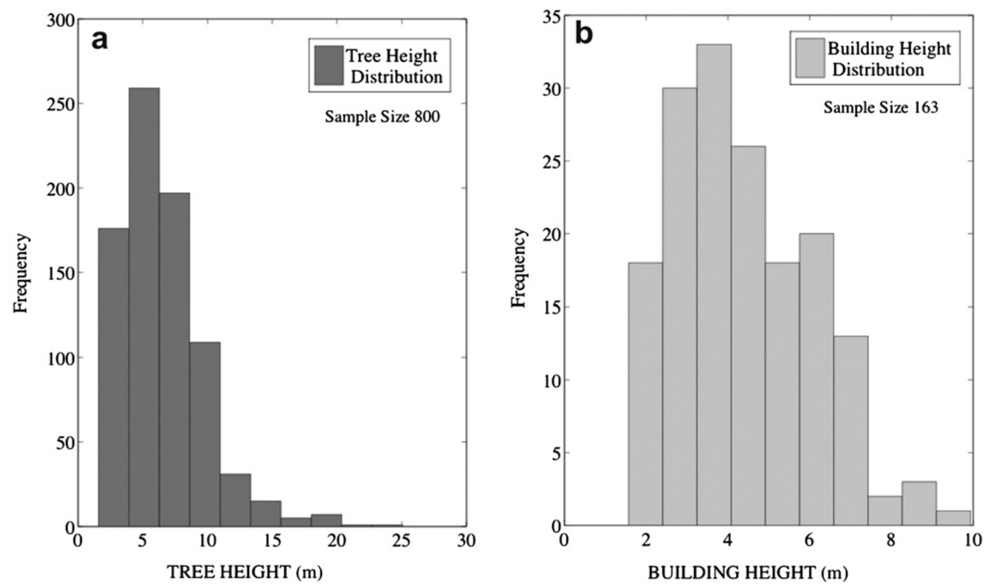

Fig. 5. Building and tree height distribution in the neighborhood surrounding the Murray (suburban) study site. (Mean tree height = 6.5 m: Mean building height = 4.4 m: Std. Dev. of tree heights = 3.2 m: Std. Dev of building heights = 1.7 m).

Laminar flow was maintained inside the tubes attached to the gas analyzers. To account for low frequency losses associated with tube attenuation, procedures described by Baldocchi et al. (2000) were followed (the spectral corrections resulted in about 25% increase in CO_2 fluxes). The CO_2, sensible and latent heat fluxes were WPL corrected (Webb et al., 1980) and Moore's correction (Moore, 1986) was used to account for system response mismatch errors. The LI-CORs sensors were calibrated for zero and span every 7–14 days manually.

Every individual raw dataset was manually checked for spikes and erroneous data points were neglected in average flux calculations. Data points when wind speeds were in excess of 10 ms^{-1}were not considered, as they are over the safe operating limits of the CSAT3 anemometers. Also, data from rainy days were avoided. No data were neglected based on a 'low turbulence' criteria, however the friction velocity (u_*) was less than 0.2 ms^{-1}about 15% of the time and less than 0.1 ms^{-1} 6% of the time. Stationarity tests were conducted for the CO_2 fluxes for the July 2005 dataset and an overwhelming majority of the data points (greater than 95%), obeyed the stationarity criteria. Spectral analysis was performed on the dataset. A −5/3 slope was observed in the power spectra of CO_2 and the vertical velocity fluctuations in the inertial subrange.

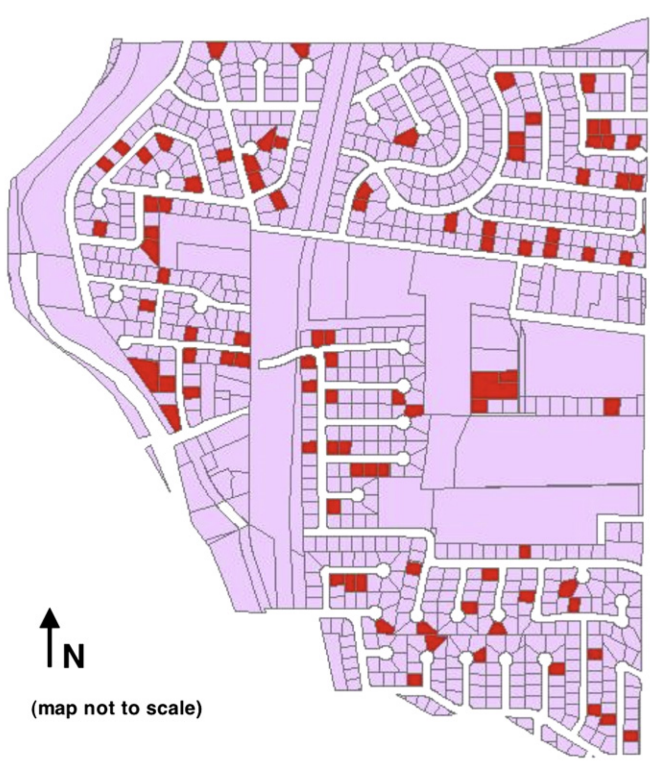

Fig. 6. Map of the Murray neighborhood. The shaded blocks indicate the houses where tree and building heights were measured manually.

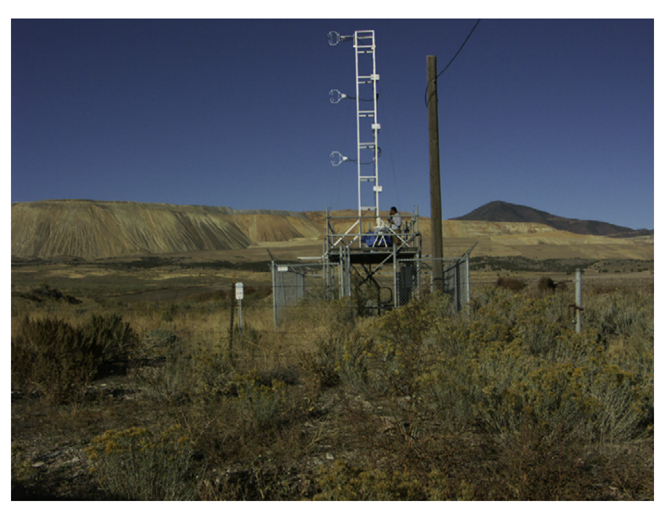

Fig. 7. Photo (looking to the north-west) of the measurement tower and vegetation surrounding the pre-urban Kenecott site.

Table 3
Measurement equipment deployed during summer 2005 observational period.

	Kenecott	Murray
CO_2 and H_2O flux	LI-COR 6260 (9 m)	LI-COR 7000 (36 m)
Wind spd, wind dir, momentum and sensible heat flux	Cam. Sci. CSAT3 (9,7,5 m AGL)	Cam Sci. CSAT3 (35.9,23.5,17.1, 12.1, 5.9 m AGL)
Humidity	Cam. Sci. HMP45C (9 m)	–
Ground heat flux	Cam. Sci HFP01SC	–
Net radiation	Kipp and Zonen CNR1 (9 m)	–
Soil heat flux ht. flx	Cam. Sci. HFP01SC	–

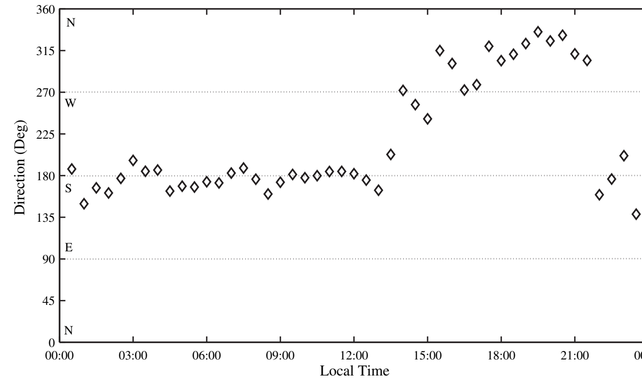

Fig. 8. 30-min ensemble averaged wind direction from the suburban site for a typical day (August 20 2005) indicating the diurnal pattern associated with the up valley and down valley winds.

5. Results

5.1. Wind direction and flux footprints

Fig. 8 shows half hour averaged wind direction data for a typical summer day at the suburban site. The plot shows a clear diurnal pattern associated with valley winds. The winds are from the south from midnight through noon the next day. In the afternoon and evening periods, winds typically come from the north-west. A flux footprint analysis can be useful in correlating these dominate wind directions with the underlying land cover. A flux footprint may be represented as a plan area (contour) surrounding the measurement location that estimates where a specified fraction of the total measured flux originates. Flux footprints were calculated for the entire summer 2005 dataset for the suburban site and for the months of August and September 2005 for the pre-urban site using the Hsieh et al. (2000) model. Figs. 9, 10 and 12 show the area responsible for 90% of the fluxes. The sector averaged footprint length for the unstable period was 738 m and for the stable period it was ~7 km, at the suburban site. Fig. 9 shows that during the unstable period, the sectors to the south and south-east of the site were more influential with winds coming from those direction approximately 66% of the time. Even at the pre-urban site (Fig. 12), the south and south-easterly sectors were more dominant. Fig. 11 shows the CO_2 flux roses for the suburban site for all time periods during the summer 2005 field experiment. It is evident that as a result of the valley wind circulation, the fluxes are dominated by sources from the south-east to south-west of the measurement tower. Smaller contributions result from winds coming from the north-west.

5.2. Daily CO_2 fluxes at suburban site

Fig. 13 shows 30-min ensemble averaged diurnal variation of summertime CO_2 fluxes at the highly vegetated Murray suburban site for three summer months in 2005. Positive half hourly averaged CO_2 fluxes were observed during the evening and nighttime periods for all three months. Midday sequestration is apparent as a result of photosynthesis from the vegetation. Maximum flux values were typically observed during the morning rush hour. An ensemble averaged maximum flux of 6 μmol m^{-2} s^{-1} was observed for August, while individual half-hourly fluxes exceeded 15 μmol m^{-2} s^{-1} (see Fig. 11). During the midday period the ensemble averaged fluxes dipped as low as −15 μmol m^{-2} s^{-1}, as seen in the July data in Fig. 13, and individual half-hourly fluxes were as low as −15 μmol m^{-2} s^{-1} (see Fig. 11). Even with the midday sequestration, the suburban site still acted as a net daily source of CO_2 for all three months. An average daily emission of 2.6 gm^{-2} day^{-1} was observed for July 2005 and this nearly doubled for August 2005.

Table 4
Measurement equipment deployed during fall 2007 observational period.

	Murray
CO_2 and H_2O flux	LI-COR 7000(35.9 m AGL)
Wind spd, wind dir, momentum and sensible heat flux	Cam. Sci. CSAT3 (35.9 m AGL)
Ground heat flux	Cam. Sci HFP01SC
Net radiation	Kipp and Zonen CNR1 (36.5 m AGL)

5.3. Seasonal variation of CO_2 fluxes at suburban site

Fig. 14 compares 30-min ensemble averaged diurnal variations of CO_2 fluxes from two different seasons (summer and early autumn). As the figure shows, nighttime fluxes are higher in fall than in summer. The ensemble averaged fall CO_2 fluxes reach as high as 6.5 μmol m^{-2} s^{-1} during the early morning hours. During the growing season (summer) we see greater sequestration throughout the midday period. The average daily emission for the summer month (July 2005) was 2.6 gm^{-2} $day^{-1}$and for the fall month (October 2007) was ~10 gm^{-2} day^{-1}.

A comparison between summer and wintertime CO_2 fluxes would have been ideal, but due to instrumentation problems we were unable to obtain flux data for the winter months. However, CO_2 concentration data were successfully obtained for winter 2008. Fig. 15 shows the daily variation of CO_2 concentration for summer and winter months. The plot shows substantially higher CO_2 concentrations for winter compared to summer. The figure also indicates that midday summer concentrations approach global background values. The average daily concentration for the summer month was 402.8 ppm whereas during winter (January 2008) it was 430.7 ppm. Although a significant variation is observed in the averaged CO_2 concentration values, the diurnal pattern remains similar for both the seasons, with the concentrations peaking during the morning rush hour.

5.4. Daily CO_2 fluxes at the pre-urban site

Fig. 16 captures the distinctly different diurnal CO_2 flux pattern observed at the two sites. The fluxes at the pre-urban site were between 0 and ~1.8 μmol m^{-2} s^{-1} during the nighttime but increased to ~6 μmol m^{-2} s^{-1} during the day with a daytime maximum of 7.8 μmol m^{-2} s^{-1}. Traffic from a nearby roadway and soil respiration are likely responsible for the positive fluxes at the pre-urban site. Unfortunately, we were unable to monitor traffic during the experiment, however Fig. 12 shows that ~80% of the winds measured at

Fig. 9. Flux footprint (90%) for the unstable period at the suburban site for summer 2005. The percentages shown indicate the fraction of time during the measurement period that the wind was coming from each 45° sector.

the tower came from portions of the flux footprint that include the neighboring roads and nearby intersection (which was within 200 m of the tower). It is also worth noting that Ivans et al. (2006) measured CO_2 fluxes from a variety of semi-arid species (including crested wheat grass and sagebrush) in an ecosystem without any anthropogenic emissions in a valley very close to the Salt Lake Valley (40.2833° N, 112.4667° W). During the summer (when the grasses were senescent), they found that CO_2 flux emissions over sage and crested wheat grass could be as high as 6 μmol m^{-2} s^{-1} (after a desert rain event) and typically ranged between −2 and 2 μmol m^{-2} s^{-1} during dry conditions. They attributed the relatively high efflux of CO_2 to microbial responses and physical displacement of CO_2 by water after rains. In comparison to the pre-urban site, the suburban site acts as a stronger source for CO_2 during the nighttime. This is mainly due to natural gas burning for residential purposes, traffic and biogenic respiration. As indicated earlier, substantial tree

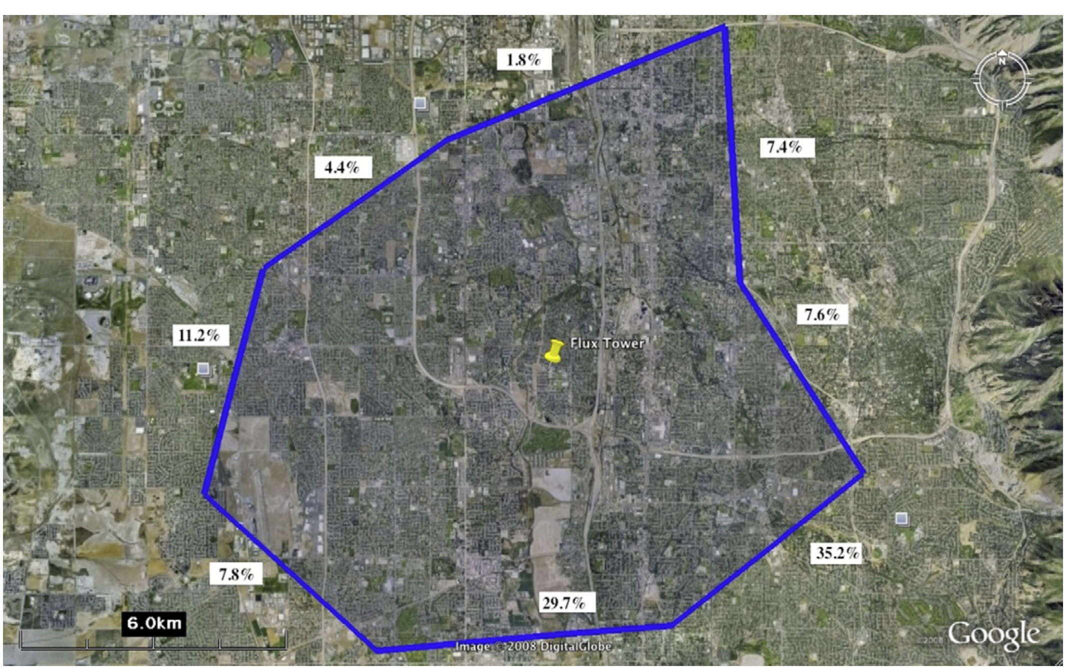

Fig. 10. Flux footprint (90%) for the stable period at the suburban site for summer 2005. The percentages shown indicate the fraction of time during the measurement period that the wind was coming from each 45° sector.

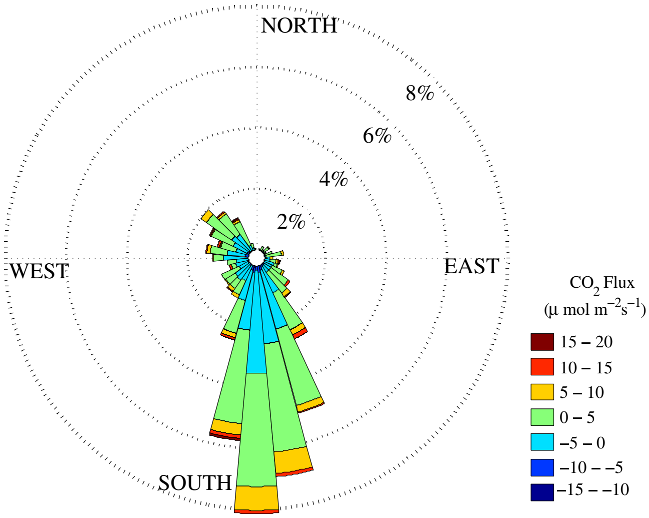

Fig. 11. Flux rose for all time periods at the suburban site during summer 2005.

cover and other vegetation around suburban site captures CO_2 during the daytime.

5.5. Average daily net CO_2 flux

Fig. 17 shows averaged daily total and nighttime CO_2 fluxes for different months at both the sites. During the summertime (June–September) at the suburban site, the total net daily CO_2 fluxes were low, on average 3.49 gm^{-2} d^{-1} and the contribution from the nighttime fluxes were high, on average more than 82% for the summer months. The nighttime relative contribution declined to about 62% at the beginning of autumn (October) at the suburban site. At the pre-urban site during summer, the nighttime contribution was low, ~13% of the overall net daily CO_2 flux. Also, the total net daily CO_2 flux at the pre-urban site during summertime was nearly three times that at the suburban site during the same period.

Fig. 12. Flux footprint (90%) for the unstable period at the pre-urban site for summer 2005. The percentages shown indicate the fraction of time during the measurement period that the wind was coming from each 45° sector.

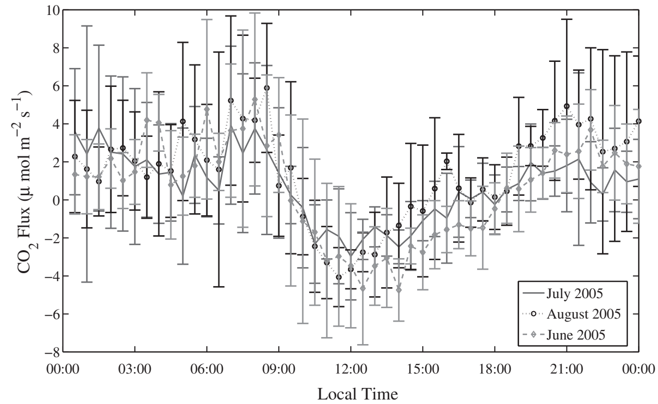

Fig. 13. 30-min ensemble averaged CO_2 fluxes and standard deviation of the fluxes at the suburban site for summer 2005.

5.6. Energy fluxes

Fig. 18 compares 30-min ensemble averaged latent and sensible heat fluxes from the suburban and the pre-urban sites for September 2005. The plot shows similar contribution from the latent and sensible heat fluxes at the suburban site (Bowen Ratio $\approx 1 - 1.5$). The data shown in the plot are from September 2005. At the suburban site, the average sensible heat flux reached a peak value of 110 Wm^{-2} and the maximum latent heat flux was ~95 Wm^{-2}. At the pre-urban site where the sensible heat flux dominates over the latent heat flux, the maximum sensible and latent fluxes were ~225 Wm^{-2} and 65 Wm^{-2}respectively (Bowen Ratio $\approx 3.5 - 4.5$).

Fig. 19 shows 30-min ensemble averaged sensible and latent heat fluxes at the suburban site for summer 2005 and fall 2007. As expected the heat flux values during summer are higher compared to fall. For both months, peak heat flux values were observed around 1400 h.

6. Discussion

The results indicate a number of impacts of urbanization on the CO_2 and energy budgets in Salt Lake Valley. Comparing the data obtained during different months has helped to explain how seasonality and human activity affects CO_2 emissions in the SLV. CO_2 fluxes from summer and early fall indicate that the suburban area acts as a sink for CO_2 during the daytime (average midday fluxes dipping as low as ~−5 µmol m^{-2} s^{-1} during summer). This

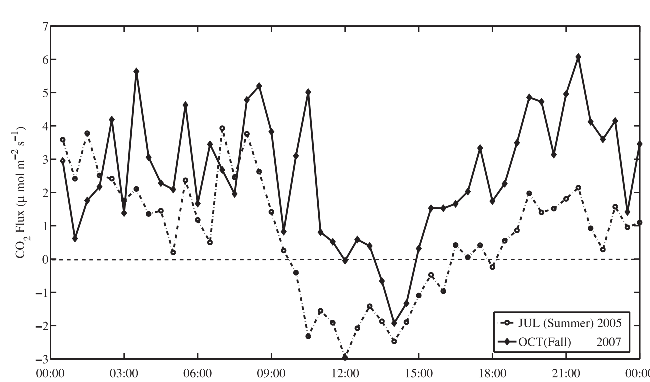

Fig. 14. 30-min ensemble averaged CO_2 fluxes from the suburban site for summer 2005 and fall 2007.

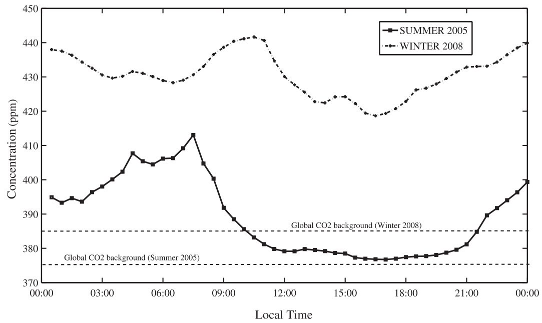

Fig. 15. 30-min ensemble averaged concentration values from the suburban site for summer 2005 and winter 2008 (Note that global background data were obtained from Tans (2008)).

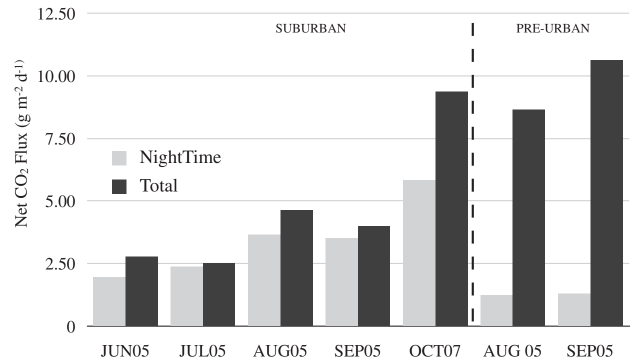

Fig. 17. Average net daily CO_2 flux for different months.

phenomenon is typically unobserved in other CO_2 flux studies conducted in urban areas due to a lack of vegetation in the tower footprint. The vegetative cover that aids in uptake of CO_2 at the suburban site is largely non-native to the valley and is a result of urban development. The suburban site is very much an urban forest with nearly 67% of the area around the suburban site covered with vegetation and pervious surfaces and an overall LAI (Leaf Area Index) of 3.6. Almost every residential and commercial facility within the fetch of the tower has irrigated lawns and deciduous trees.

Figs. 9 and 10 show the averaged flux footprint for the unstable and stable period at the suburban site for the summer months. The fetch area to the south and south east of the tower accounted for nearly 65% of the fluxes during the unstable and stable period. The land cover is very heterogenous in these sectors. The area consists of irrigated open play grounds, residential houses, tree cover, commercial roof-tops and residential roads. The area to the north and north-east of the measurement site, where the land cover was relatively uniform, had a lesser influence on the tower during the unstable time periods. Fig. 11 also supports the above concept, the plot compares CO_2 fluxes with wind direction at the suburban site for the entire 2005 summer experiment. The area to the south, south-east, south-west and north-west appear to be the most dominant wind directions to influence the tower.

Comparing the CO_2 fluxes from summer and fall, we see reduced sequestration during the fall season. The average daily CO_2 emission values increased from 2.6–5.4 $\mathrm{gm^{-2}\ day^{-1}}$ in summer to $\sim 10\ \mathrm{gm^{-2}\ day^{-1}}$ in fall. The increase in net daily emission is a result of reduction in sequestration due to decline in canopy cover and also due to an increase in natural gas consumption as a result of increased heating demand. Fig. 20 shows the natural gas consumption at the suburban site increased from 1877 DTherms during summer months to 2672 DTherms in fall (Data for Fig. 20 was obtained from the local natural gas supplier Questar). There is also a tenfold increase in natural gas consumption during the winter months. The suburban site is also close to an intersection of two major freeways (I-15, I-215) that run through the valley. Heavy traffic is observed on these freeways throughout the day and hence a contribution is expected from them depending on the extent of the flux footprint.

The CO_2 concentration values, shown in Fig. 15, are higher for all time periods during winter compared to summer. This is mainly due to higher natural gas usage during the winter months and a reduced mixing volume. In the winter months, the Salt Lake Valley experiences extended periods of inversion also known as *Persistent Cold Air Pools* (PCAPs). PCAPs are defined as a topographically confined, stagnant stably stratified layer of air that is colder than the air above (Whiteman et al., 2001; Sivasamudram, 2009). Due to the PCAPs, CO_2 emitted on a daily basis can be confined to the valley for several days (Pataki et al., 2005). Concentration values as high as 570 ppm were observed during January 2008.

Comparing the CO_2 fluxes from the suburban and the pre-urban sites, we see the pre-urban site acting as a source of CO_2 during the midday period. As noted above, we hypothesize this is mainly due to traffic along a roadway nearby the site and microbial respiration. The area around the pre-urban site contains neither irrigated surfaces nor residential housings. The flux footprint for the unstable period at the pre-urban site indicates that the sector to the south-east and south of the tower were more influential

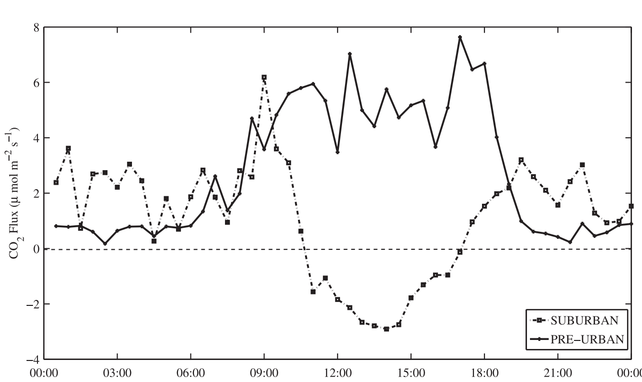

Fig. 16. 30-min ensemble averaged CO_2 fluxes from the suburban and pre-urban site for fall 2005.

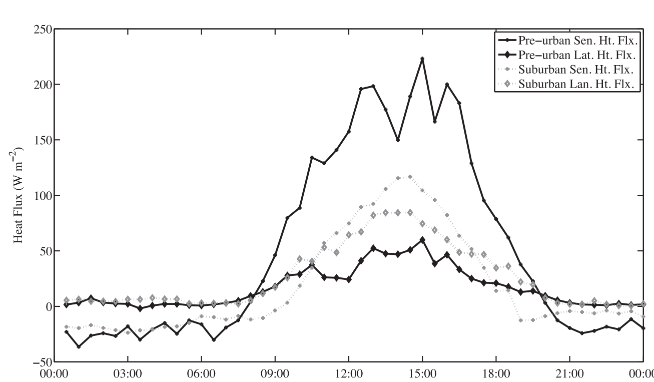

Fig. 18. 30-min ensemble averaged latent and sensible fluxes from the suburban and pre-urban site for fall 2005.

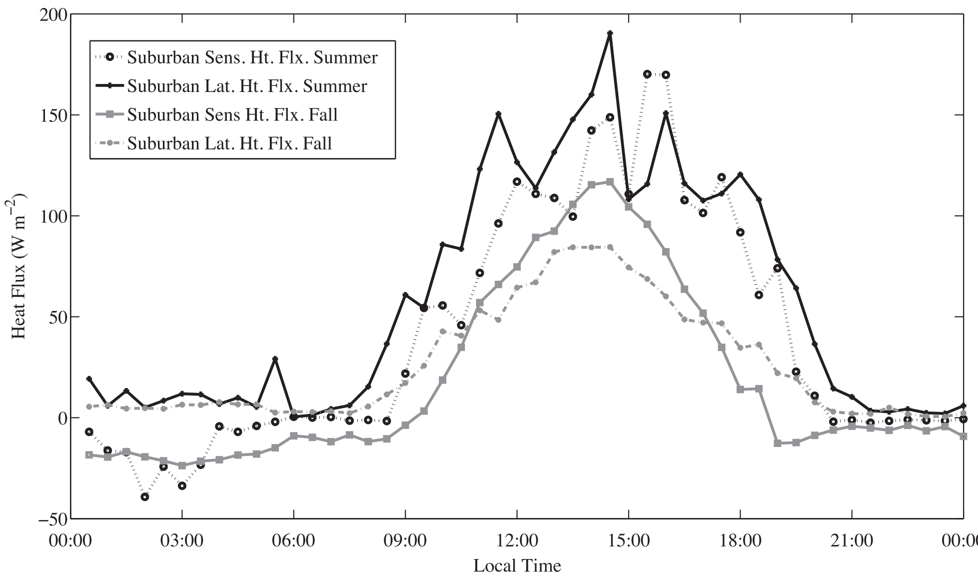

Fig. 19. 30-min ensemble averaged latent and sensible fluxes from the suburban site for summer and fall 2005.

(accounting for ∼55% of all the fluxes). A roadway carrying heavy trucks for a major mine operating nearby runs through these sectors. The sector to the south-east of the tower also has a busy intersection. As the traffic dies down during the nighttime, the CO_2 fluxes dip close to zero.

The land cover characteristics around the pre-urban site resemble the SLV before development within the urbanized valley. The comparison study has enabled us to gain understanding regarding the impact of urban development in the valley. While the CO_2 fluxes are small at the pre-urban site during the nighttime, anthropogenic emissions and plant respiration contributes heavily during the nighttime at the suburban site. The urban forest around the suburban site sequesters CO_2 during the daytime thereby bringing the overall net CO_2 emissions down. Even with significant sequestration, the suburban site still acts as a source of CO_2 during the summertime. This is consistent with the modeling results from the UTES study (Pataki et al., 2009).

The impact of urban development was also observed in the energy fluxes. Similar contributions from latent and sensible heat fluxes were observed at the suburban site during the summer months. The urban forest around the site releases water vapor into the atmosphere through transpiration and reduces the potential sensible heat fluxes. At the pre-urban site though, sensible heat fluxes are much higher compared to latent heat fluxes and similar to those observed naturally in Utah (Ivans et al., 2006). Comparing the heat fluxes during the summer and fall seasons, we see that as the growing season wanes, the contribution from latent heat flux also declines.

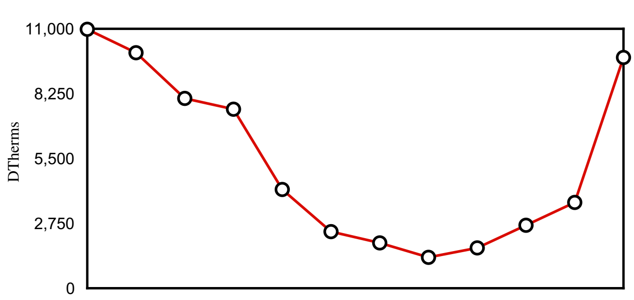

Fig. 20. Natural gas consumption for different months of 2005 for the suburban site (Source: Questar).

7. Conclusion

The Salt Lake Valley urban flux study has added to the general understanding of the behavior of CO_2 fluxes in cities by adding knowledge regarding semi-arid cities. The study focused on two sites with distinct urban forms: a rural grass/shrub-land pre-urban site and a highly vegetated suburban site. Since the two sites are located within the same valley and experience similar large scale climatology, the resulting analysis provides an indication of the impact of urbanization on CO_2 fluxes as well as sensible and latent heat fluxes. This study has provided a detailed summary of the surrounding land form which is critical to understanding the processes contributing to the surface fluxes. We have reported urban land form details such as the distribution of building and tree heights as well as tree species fraction, as future models are likely to require such detailed surface information.

During the summer, the variation in the behavior of CO_2 fluxes at the pre-urban and suburban sites were somewhat unexpected, as the suburban site was a larger sink than the pre-urban site. This was partially a result of the non-native urban forest that dominates the suburban area. The suburban forest also substantially altered the surface energy budget leading to larger latent heat fluxes and smaller sensible heat fluxes at the suburban site (resulting in a much more comfortable microclimate). The average net daily CO_2 flux for the summer months at the suburban site was ∼3.5 gm^{-2} d^{-1}, whereas at the pre-urban site the value was around ̃10 gm^{-2} d^{-1}. These results are expected to be relatively unique to semi-arid regions where the natural grasslands are largely dormant during the summer months.

From Fig. 1, it is evident that there is a strong correlation between CO_2 fluxes and vegetative fraction, which in turn should be related to the density of the urban form, during the summer months in urban environments. Here, for urban form we use the definition of (Anderson et al. (1996) Anderson, Kanaroglou, and Miller) which defines urban form as ‘the spatial configuration of fixed elements within a metropolitan region. This includes the spatial pattern of land uses and their densities as well as the spatial design of transport and communication infrastructure.’ It should also be noted that apart from sequestration, indirect effects on building energy consumption, such as heating and cooling demand-changes due to sheltering and shading also affect CO_2 emissions in urban areas.

Data from our study show that the urban forest in a semi-arid climate considerably increases carbon sequestration during the summer months. However, this increased carbon uptake may have limited impact on the total carbon budget due to the duration of the growing season and the magnitude of emissions during the non-growing season. Hence, the sequestered carbon is still only a small fraction of the total emissions. For example, the modeling work in Pataki et al. (2009) showed that increasing the number of trees in the SLV by 1.2 million between 2005 and 2030 only resulted in a 0.2% reduction in net emissions by 2030. This may be an indication that mobility in Fig. 1 is fairly limited, however this hypothesis should be investigated in much greater detail. We also propose that the underlying processes that contribute to CO_2 emissions in semi-arid urban environments need to be studied in more detail.

Acknowledgements

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