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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 μmol 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

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 μmol m^{-2} s^{-1}. Summertime fluxes measured in Melbourne, Australia (Coutts et al., 2007), varied between 2 and 14 μmol m^{-2} s^{-1}, while in Tokyo (Moriwaki and Kanda, 2004), the CO_2 fluxes varied between 4.5 and 11.4 μmol 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 μmol 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

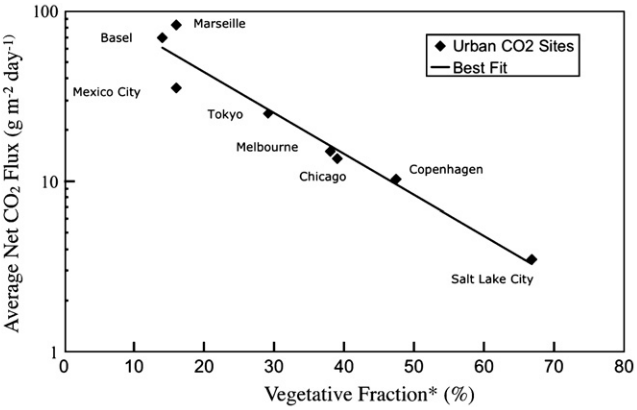

Fig. 1. Variation of the average daily net CO_2 flux for different cities around the world during the summer months as a function of vegetative land cover. The curve is an exponential function of the form $y = Ae^{-b}$, where $A = 132$ gm^{-2} day^{-1}and $b = 0.055$ with an $R^2 \sim 0.95$. *Note that 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.

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 μmol 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