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Eddy Covariance Measurements of CO_2 Flux Over an Urban Area in North Alabama

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Abstract- Measurements of the atmosphere-surface exchange of gases over urban areas are a way to evaluate emissions inventories, and to better understand urban atmospheric chemistry. The objective of the present study was to quantify the net CO_2 exchange of residential areas of varying density in the urban setting and biological sources and sinks on the net CO_2 fluxes. Measurements of carbon dioxide flux (Fc), the latent and sensible heat fluxes were performed using the eddy covariance (EC) method in Huntsville, Alabama over a 2-yr period in 2013–2014. The EC setup was installed at a height of 17m on the meteorological tower in the southeast part of the city. Both on diurnal and monthly scale, the urban surface acted as a net source of CO_2 and downward fluxes were only occasionally observed especially in spring of 2014. The source area of Fc was highly heterogeneous, which consisted of buildings, parks, and highways. Other anthropogenic activities at the site had the impact of enhancing the flux of CO_2 especially in 2013.and early part of 2014when the study site was heavily disturbed by construction works. On seasonal scale, Fc was higher in winter than other seasons likely due to domestic heating during colder months. Spring and fall were two transition periods of the turbulent fluxes. Total annual average CO_2 emissions from the neighbourhood of the tower were estimated to be 655g C m^{-2}.

Keywords: Anthropogenic emission, Carbon dioxide flux, Fossil fuel, Latent heat, Sensible heat, Urbanization.

1. Introduction

The proportion of the world's population living in urban areas has increased over the past several decades and urbanization is expected to increase significantly in the coming decades as populations and economic activity continue to grow [1]. The growth of the human population has yielded cities of unprecedented size, extent, and form [2;3], that emit significant quantities of waste transform habitats modify major biogeochemical cycles alter local climate and impact human health.

Humans have always interacted with the biophysical environment since the beginning of human history, but the magnitude, complexity, and implications of these interactions have increased dramatically in recent decades [4]. One of the most important impacts of urbanization on local and regional climates is the changes in land use, and emissions associated with the combustion of fossil fuels (primarily CO_2) to the atmosphere [5]. Urban areas emit 30–40% of all anthropogenic greenhouse gases, even though they currently cover only about 4% of the world's dry land surface. CO_2 is one of the most important greenhouse gases and a significant increase in CO_2 concentrations (from 280 ppm in pre-industrial times to 387 ppm in 2009) is the probable cause of the mean air temperature increase of approximately **0.85ºC** observed during the last 100 years [6].

Urban development choices play a central role in determining local, regional, and global carbon emissions (via factors such as land clearing, energy consumption, and transportation) and terrestrial carbon sinks (via vegetation carbon storage and uptake) [7]. However, knowledge of the magnitude and temporal variability of surface-atmosphere CO_2 exchange in cities has been limited up until the recent years. Although it is abundantly clear that cities and urbanizing areas affect local and global sinks and sources of

CO_2, the exact magnitude of and mechanisms for carbon exchange remain highly uncertain for urbanizing regions [8].

The process of urbanization itself typically results in substantial emissions due to the land clearing and construction activities. Most developed lands typically have some level of vegetation returned after construction (from road median planting strips and greenbelts to residential landscaping and gardens), but urban expansion results in complex patterns of intermixed high- and low-density built-up areas and a fragmentation of the natural landscape. The complex interactions between urbanization and vegetation functions are influenced by both human and biophysical factors (Biotic and abiotic) and competing positive and negative feedbacks among them [9]. The aggregated effects of urbanization on land–atmosphere exchange processes remain highly uncertain despite decades of study on components of the problem [10].

The net CO_2 exchange from urban ecosystem results from the combination of emissions from fossil fuel burning and from sources and sinks of biological origin [8]. Net CO_2 exchange depends on climate conditions, characteristics of the built environment and human behavior; each regulating the temporal variability of biological (vegetation and animal metabolism) sources and sinks as well as fossil fuel emissions [11]. CO_2 fluxes have been quantified for a limited number of cities around the world.

The limited urban EC studies have mainly focused on cities in developed countries [12;13]. The characteristics of urban CO_2 exchange in developing economies, where the degree of industrialization is relatively lower than that in developed economies, are largely unknown, with the only reported measurements from Mexico City nd Cairo [14]. Such studies have typically focused on anthropogenic CO_2 emissions from fossil fuel burning. Hence, long-term observational studies reporting on the annual and seasonal variation of net CO_2 exchanges as well as on the environmental drivers that can affect CO_2 fluxes are still lacking.

2. Materials and Methods

2.1. Measurement site and study period

The flux measurements were conducted from a 17m tower mounted on the north-west end of the Huntsville High school. Huntsville High School is located in the downtown area of Huntsville in Northern Alabama. The measurement height was more than 2 times the mean height of the surrounding buildings (zh = 8m), and of sufficient height to be in the constant flux layer. The flux system was located in a busy district within the geographical coordinates of 34º42'N 86º35'W34.700ºN 86.583ºW (34.7300° N, 86.5850° W) and 189.9.m above sea level) surrounded by congested avenues and close to the center of the city.

This site is one of the oldest residential areas in the city. The surrounding topography is flat and relatively homogeneous in terms of building material, density, and height. The aerodynamic surface roughness was estimated to be zo = 1m and the zero displacement plane was calculated to be 5.6 m height following the rule-of-thumb estimate, where zd = 0.7zh [15].

The predominant land use was residential and commercial, with only the school buildings (built of concrete) of two and three stories height on the eastern side of the tower. (Figure.5.1). The number of CO_2 anthropogenic sources was large, and composed of a mix of commercial, residential and mobile sources.

2.2. Eddy Covariance Instrumentation

The Eddy covariance setup at the HHS consisted of the CSAT-3, a Sonic Anemometer (CSI, Logan, Utah), to measure wind speed (m s^{-1}) in three-dimensional space, and sonic air temperature (T_s, ºC); LI-7500 Open Path (OP) CO_2/H_2O infrared gas analyzer (IRGA) (LI-COR Inc., Lincoln, NE) to measure CO_2 and water vapor fluctuations as well as a CSI CR5000 Datalogger for data storage. The IRGA was slightly tilted (~ 15º from the vertical axis of the IRGA) to prevent rainwater accumulation and dew deposition on the measuring window and was displaced 0.15 m behind the CSAT-3, facing the dominant prevailing winds. Both instruments were operated at a sampling frequency of 10 Hz. Other Meteorological and canopy parameters to help validate and interpret Eddy flux data included net radiation and humidity sensors.

The data acquisition system, Data Logger (CR5000, Campbell Scientific Inc., Logan UT) collected high frequency data from the sonic anemometer, gas analyzer and other sensors and was storing days of binary formatted data on a Memory Card International Association (MCIA) flash card.

2.3. Data Processing and Analysis

In this study the EC data were analyzed over a two-year period (2013 to 2014). The turbulent vertical flux density of a scalar (Fc) was calculated as being proportional to the covariance between the vertical wind velocity (w) and the scalar concentration (c) of interest according to the eddy covariance technique [16].

$$Fc = \rho a w^{/} c^{/} \quad \overline{} \qquad (1)$$

M'Parkway Bob Wallace Road

Location of monitoring tower at HHS

Figure 1. Aerial view of HHS and the surrounding features.

where: Fc (measured in μmol $m^{-2}s^{-1}$ or mg $m^{-2}s^{-1}$) is the gas flux (CO_2), ρa is the air density, w, the vertical wind velocity and c, the scalar concentration while the primes represent fluctuations from the mean [17], and the over bar represents a 30 minutes time averaging in compliance with most micrometeorological experiments. Formula for the Sensible heat (H) and Latent heat energy (LE) fluxes both measured in Wm^{-2} are:

$$H = \rho\overline{a,C_p w}´T' \qquad (2)$$

$$LE = L\overline{W'\rho'v} \qquad (3)$$

where: ρa is the air density, C_p is the specific heat at constant pressure (in J $kg^{-1}K^{-1}$), T the air temperature, L the latent heat of vaporization for water (in J kg^{-1}), ρv the water vapour density and w, again the vertical wind velocity (ms^{-1})

Before calculating the half-hourly fluxes of CO_2, data processing using the EddyPro software package (from Li-COR Inc.) and then followed by analysis was carried out. The first steps in the EC data processing and analysis were unit conversion and spike removal from the recorded raw data. Further corrections by the same software package and manual operation were also carried out. By this water vapor, sensible heat and momentum, spike detection and data rejection algorithms were applied using dynamic mean and standard deviation values within a series of moving windows as described by [18]. Some obvious spikes (due to both electronic and physical noise) which the spike detection procedure failed to identify were removed manually. Coordinate rotation of data (due to imperfect levelling of the sonic anemometer took place using a double rotation procedure so that the mean vertical velocity was set to zero [19]. Theoretical spectral corrections (from loss of fluxes at different frequencies (eddy sizes) made for high-frequency losses due to sensor separations, path averaging and sensor frequency response increased flux values. The water vapour and CO_2 fluxes were also corrected for the density fluctuations.

Data quality was assessed by using the steady state test and integral turbulence characteristic test suggested by [20]. Data not passing the tests were excluded from the analysis. Nocturnal fluxes in non-urban ecosystems are known to be underestimated by EC measurements due to the low-turbulence conditions prevailing at night [21]. The friction velocity (u*) filtering approach developed for non-urban areas is problematic in urban areas because the urban boundary layer is not always stable at night due to anthropogenic heat emissions, releases of storage heat to the boundary layer, and the heterogeneity of the urban canopy [22]. An appropriate u* threshold is difficult to determine for its variation and uncertainty. More errors may be introduced into the calculation of annual total flux when using this approach. Therefore, no u* filtering was applied in this study. The storage term was omitted because the profile of CO_2 concentration in the canopy was not measured. On the other hand, it is considered that the storage term was minor in the calculation of annual total CO_2 emission [22].

Data gaps originating from power failures, instrument calibration errors, or sensor malfunctions accounted for 16% during the two-year study period. Out-of-range data removal and spikes detection (outside 3 times of standard deviation from mean value) removed extra 3% of data. Low-quality data caused by precipitation, dust, or other contamination on the sensor optics, resulted in 6% of eliminated data. Data that failed the stationary test caused another 6 % of the data gaps. Overall, the data coverage for the study period was approximately 69 %.

Missing data were reconstructed by using a gap-filling strategy as follows: (1) small gaps (< 2 h) were replaced with linear interpolations; (2) medium gaps (< 2 days) were rebuilt based on the mean diurnal variation (MDV) on adjacent days [23]; and (3) large gaps (>2 days) were rebuilt using a multiple imputation (MI) method following [24]. For Fc, related meteorological variables, such as air temperature, wind direction, and day of week etc., were input in the imputation. Weekend and weekday were distinguished when using MDV and MI method. If the gaps occurred in the weekend, the gaps were not filled by MDV method, but they were filled by the MI method which considered most of the relative meteorological factors.

3. Results and Discussion

3.1 Meteorological conditions

Meteorological conditions in Huntsville for the two years of the study are shown in Figures 2a and b. The average temperatures for the two years under investigation ranged from 43 °F (6.2 °C) in January of 2014 to 80 °F (26.5 °C) in July of 2013. Mean monthly temperatures in the Huntsville area typically range from 38 °F (3 °C) in January to 78 °F (26 °C) in July (Retrieved from http://countrystudies.us/united-tates/weather/alabama/huntsville.htm). In general, the two years of the study was warmer than average for the area.

During the same time, precipitation by way of rainfall ranged from 0.2 in (6.1 mm) in April of 2013 to 9.7 in (247 mm) in August of 2013. But mean monthly averages in the area typically ranged from 3.3 in (83 mm) in August to 6.6 in (167 mm) in March (National Climatic Data Center (NCDC); retrieved from: www.sercc.com/climateinfo_files/monthly/Alabama_temp.html). Whereas the temperatures at the study site reflected long term averages for the area, there was wide departure in rainfall of the site from normal averages, especially for 2013. During the two-year study, the lowest rainfall of 0.2 in (5.1 mm), and the highest rainfall of 9.7 in (246.4 mm) were both recorded in 2013. This high variability in rainfall is likely to affect the C flux patterns of the area.

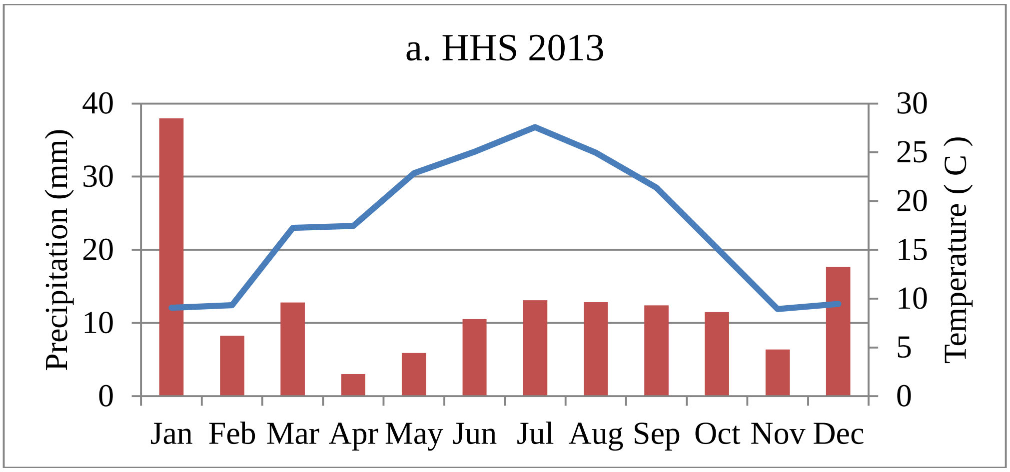
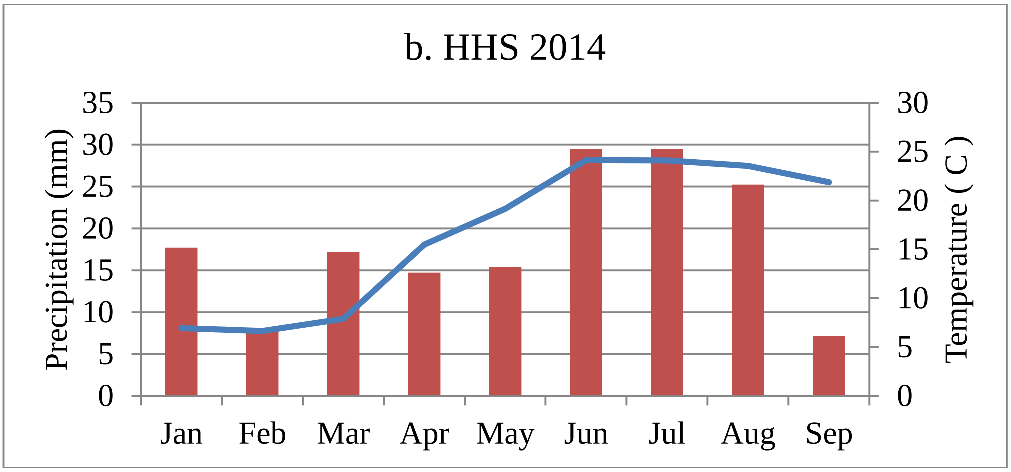


Figure 2.a. Temperature and precipitation records of Huntsville in 2013.



Figures 2.b. Temperature and precipitation records of Huntsville in 2014.

3.2. Annual net CO_2 exchanges

Average monthly Fc ranged from 0.003 mg m-^{2} s-^{1} in May to 0.16 mg m-^{2} s-^{1} in December of 2013. The lowest recorded values for 2013 were between April and May, and the highest recorded values were between October and December. The average monthly Fc was always positive regardless of the month in 2013 (Figure 3a). In 2014 average monthly Fc ranged from 0.0024 mg m-^{2} s-^{1} to 0.15 mg m-^{2} s-^{1}. Fc was near zero in May and July of the year having the lowest average values of 0.0024 mg m-^{2} s-^{1} and 0.0018 mg m-^{2} s-^{1} respectively (Figure 3b) unlike 2013 (Figure 3 c). In 2014 highest monthly average emissions of 0.1507 mg m-^{2} s-^{1} and 0.1508 mg m-^{2} s-^{1} were recorded in January and February respectively.

The annual total CO_2 emissions for this site ranged from 256.03 mg C m^{-2} in 2014 to 675.67 mg Cm^{-2} in 2013 during the study period. The higher value recorded in 2013 could be attributed to the higher level of anthropogenic emission from the disturbance which took place for longer period in the year; and despite the relatively sequestration of CO_2 probably by the surrounding vegetation between spring and summer seasons of 2014 after the disturbance (Figures 3b) the urban surface was still a net source of carbon dioxide annually in the city

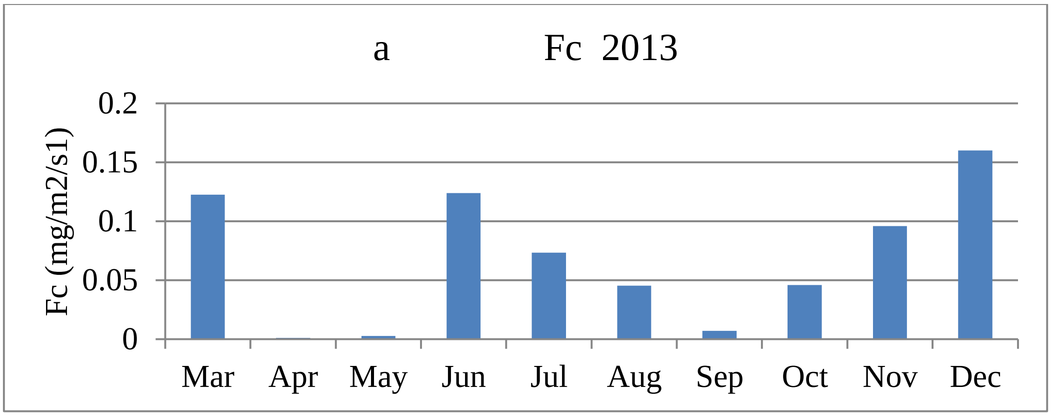


Figure 3a: Monthly Averaged Fc for the two years measured at HHS in 2013.

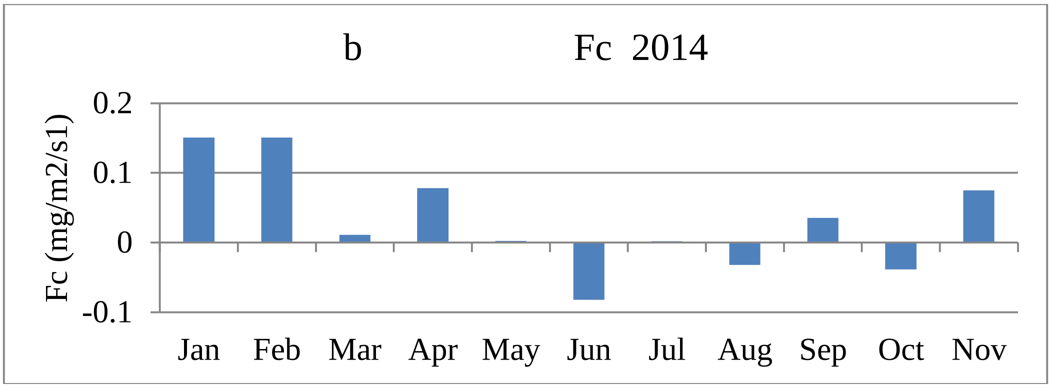


Figure 3b: Monthly Averaged Fc for the two years measured at HHS in 2014.

A major disturbance of this urban ecosystem during the study period that might have impacted CO_2 flux of the study site was urban construction (Fig. 4). Construction works at the high school involved excavations with heavy equipment that generated high anthropogenic emissions from the fossil fuel combustion of the numerous large machines in use. The heavy dust generated daily could interfere with the functioning of the CO_2 gas analyzers at the site.

Figure 4. Major disturbance at the study site.

Early in 2013 a lot of construction equipment was in operation for construction works. Activities which temporarily stopped in May were resumed in June with decreasing intensity until towards the end of the year and first quarter of 2014. The work was completed by the end of April 2014 after which trees and grasses were planted at the site. During the period of the construction work the fossil fuel burnt by the operation of the various machines in use might have contributed to the enhanced CO_2 emission. In March 2013 at the commencement of the construction work Fc average value was 0.122mg $m^{-2}s^{-1}$ compared with the 0.0029 mg $m^{-2}s^{-1}$ recorded in May of the same year when work temporarily stopped. Similar trend was observed as work resumed resulting into enhanced CO_2 emission. Fc average values in January and February 2014 were 0.15 mg $m^{-2}s^{-1}$ compared to -0.08 mg $m^{-2}s^{-1}$ recorded for June after work completion and the imported grown up trees and grasses were in place. During this time and later months, the site was actually gaining carbon reflecting the impact of the surrounding vegetation. (Figure 3b)

In addition to the effect of urban disturbance on CO_2 flux, the annual variation of Fc was characterized by an annual time course that varied inversely with air temperature. A negative correlation of -.793 between the average monthly Fc and average monthly air temperature was observed. We hypothesized that in midsummer, when the air temperature became highest, the leaf area index of surrounding vegetation probably reached its maximum and the most significant CO_2 uptake occurred. Therefore, Fc decreased as air temperature increased.

Also, space heating that occurred in winter and early spring in Huntsville might have something to do with regional CO_2 flux. Combustion of fossil fuel by traffic and heating systems were considered as the major sources of CO_2 emission in this period. The lower temperatures of the season mean more fuel used for heating. As temperatures increased, reduction in heating and CO_2 uptake through photosynthesis by vegetation might have contributed to the lower Fc.

The vegetation component played a significant role in the diurnal variability of CO_2 fluxes over the urban site. In spring and summer, the study site showed marked daytime uptake. Vegetation cover in urban areas can strongly affect CO_2 fluxes [25] and urban green spaces, including trees, shrubs, and grass, have been reported to act as an annual CO_2 sink of about 3-5 Tonnes CO_2 $ha^{-1}$of green space in Chicago, Il. Hence, the greater vegetated surface area at our urban site promoted a stronger sink capacity of the biological component while limiting spatial density of other sources and their emissions.

This result highlighted the role of perennial vegetation, especially grass and conifers for which CO_2 uptake could begin before deciduous tree and shrub leaf out and the early start of CO_2 uptake could help offset emissions from other sources. This could probably have accounted for the relatively lower cumulative values for 2014 after the completion of construction works earlier in the year unlike in 2013 which was dominated by the anthropogenic emissions of fossil fuel combustion from the numerous equipment being used for the construction work. Beside this emission there was huge excavation of soil. The heavily disturbed earth released abundant CO_2 into the air and this action could be responsible for the positive Fc in all the months of 2013

4. Conclusions

Summer CO_2 fluxes were dominated by vegetation sources and sinks as daytime CO_2 uptake occurred and CO_2 fluxes responded to incoming light levels and air temperature in a fashion similar to natural ecosystems. The positive daytime CO_2 flux (emission) was partly moderated by urban vegetation in the warm season. The consistently positive CO_2 flux throughout the year 2013 and the net positive CO_2 flux in 2014 indicated that the analyzed urban surface is a net source of CO_2 to the atmosphere. The two years were net sources of about 675.67 mg C m^{-2} yr^{-1} and 256.03 mg C m^{-2} yr^{-1} in 2013 and 2014 respectively; and, the integrated annual net CO_2 exchange over the 2-yr period calculated from a gap-filled Fc dataset was 465.85mg C m^{-2} yr^{-1} on the average. This amount translated to 655g C m^{-2} or 585,69846Kg C $yr^{-1.}$ Emissions from domestic heating were a considerable source of CO_2 in the winter. CO_2 sequestration by urban vegetation was not sufficient to offset emissions from local sources. Spatial variation patterns of CO_2 flux were mainly determined by the prevailing surface cover within the flux source area. This study showed an application of the eddy covariance technique for long-term monitoring of CO_2 flux in a densely built urban area.

Although hydroelectricity is the main energy source in the city, combustion of fossil fuels and wood for heating appeared to contribute significantly to the annual net CO_2 exchange of both years as CO_2 fluxes increased with decreasing air temperature in winter. Hence, biological sources and sinks appeared to be a dominant component of the net CO_2 exchange of the site, particularly in summer of 2014, while human activity seemed to dominate CO_2 fluxes at the site in 2013 and earlier part of 2014 by virtue of the disturbances that took place at the site.

This study showed that the use of Eddy covariance and other micrometeorological techniques to measure integrated CO_2 fluxes over urban areas could permit the monitoring of sources for which other methods such as inventories might not be suited for. For example, the vegetation component can be difficult to upscale from point measurements in an environment with complex structure and geometry such as cities. The urban CO_2 flux measurements presented here can provide valuable information for validating emission inventories used for air quality and emission models. Such measurements can prove to be critical in partitioning CO_2 emissions from different sources, especially for heterogeneous or well-vegetated environments.

References

[1] Foley, J. A., DeFries, R., Asner, G. P. *Global consequences of land use. Science*, 2005:309:570–574.

[2] Decker, E. H., Elliott, S. Smith, F. A., Blake, D. R., Rowland, F., S. Energy and material flow through the urban ecosystem. *Annual Review of Energy and Environment*, 2000; 25:685–740

[3] McDonald R. I, Kareiva P, Forman R. T. T. The Implications of current and future rbanization for global protected areas and Biodiversity conservation. *Biological Conservation*, 2008:141:1695–1703.

[4] Liu, J. G., Dietz, T., Carpenter, S.R. *Complexity of coupled human and natural systems Science*, 2007: 317, 1513–1516.

[5] Kalnay, E. and Cai, M. Impact of urbanization and land-use change on climate, *Nature* 2003:423:528–531.

[6] IPCC 2007 Climate change. Climate change impacts, adaptation and vulnerability. Working Group II. Geneva, Switzerland: *IPCC* 2007.

[7] Alberti, M. Integrating Humans and Ecological Processes in urban ecosystems. Springer, New York. *Advances in Urban Ecology*:2008.

[8] Pataki, D. E., Alig, R. J., Fung, A. S. Urban ecosystems and the North American carbon cycle. *Global Change Biology*: 2006; 12:2092–2102.

[9] Grimm, N. B., Foster, D., Groffman, P. ecosystemresponses to urbanization and pollution across climatic and societal gradients Frontiers in Ecology and Environment. *The changing landscape*, 2008:6:264–272.

[10] Pouyat, R., Yesilonis, I. D., Nowak, D. J. Carbon storage by urban soils in the United States. *Journal of Environmental Quality*, 2006. 35:1566–1575. progress and challenges. Ecohealth 4, 352-362.

[11] Cervero, R., Murakami, J. Effects of built environments on vehicle miles traveled: evidence from 370 US urbanized areas. *Environment and Planning*, 2010. A 42:400-418.

[12] Grimmond, C. S. B., King, T., Cropley, F., Nowak, D. and Souch, C. Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago, *Environmental Pollution*, 2002;116: S243–S254.

[13] Nemitz, E., Hargreaves, K. J., McDonald, A. G., Dorsey, J. R., and Fowler, D. Micrometeorological measurements of the urban heat budget and CO_2 emissions on a city scale, *Environmental Sciences and Technology*, 2002:36:3139–3146.

[14] Burri, S., Frey, C., Parlow, E. and Vogt, R. CO_2 fluxes and concentrations over an urban surface in Cairo/Egypt.The seventh International Conference on Urban Climate, Yokohama, Japan 2009.,

[15] Grimmond, C. S. B. and Oke, T. R. Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of Applied Meteorology*, 1999; 38:1262–1292.

[16] Lee, X., Massman, W., and Law, B. A guide for surface flux measurement and analysis, *Handbook of micrometeorology*: Kluwer, Dordrecht, The Netherlands, 2004. 50 pp.

[17] Baldocchi, D., Meyers, T. Trace gas exchange above the floor of a deciduous forest. Evaporation and CO_2 efflux. *Journal of Geophysical Research* 1991; (96):7271-7285.

[18] Vickers, D. and Mahrt, L. Quality control and flux sampling problems for tower and aircraft data, *Journal of Atmospheric and Ocean Technology*. 1997: 14:512–526.

[19] Kaimal, J. C. and Finnigan, J. J. Atmospheric boundary layer flows: Their structure and measurement, Oxford University Press, New York, USA, 1994:289 pp.

[20] Foken, T. G., Ockede, M., Mauder, M., Mahrt, L., Amiro, B. and Munger, W. Post-field data quality control, in Handbook of Micrometeorology: A guide for surface flux measurement and analysis, edited by X. Lee, W. Massman, and B. Law, Kluwer, Dordrecht, The Netherlands 2004.:181–208,

[21] Aubinet, M. Eddy covariance CO_2 flux measurements in nocturnal conditions: An analysis of the problem, *Ecology Application*. 2008;(18):1368–1378.

[22] Crawford, B., Grimmond, C. S. B., and Christen, A. Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area, *Atmospheric Environment*. 2011; (45):896–905.

[23] Falge, E., D., Baldocchi, R., Olson, P., Anthoni, M., Aubinet, C., Bernhofer, et al. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agric. For. Meteorol.* 2001: (107):43–69. doi:10.1016/S0168-1923(00)00225-2

[24] Hutchinson, J.J., Campbell, C.A., Desjardins, R.L., 2007. Some perspectives on carbon sequestration in agriculture. Agricultural and Forest Meteorology 142, 288–302.

[25] Vesala, T. J. A., Rvi, L., Launiainen, S., Sogachev, A., Rannik, U., Mammarella, I., Siivola, E., Keronen, P., Rinne, J, Riikonen, A. N. U. and Nikinmaa, E. 2008. Surface-atmosphere interactions over complex urban terrain in Helsinki, Finland, Tellus, 60B:188-199.