Five-years of microenvironment data along an urban-rural transect; temperature and CO_2 concentrations in urban area at levels expected globally with climate change.

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Abstract

The heat island effect and the high use of fossil fuels in large city centers is well documented, but by how much fossil fuel consumption is elevating atmospheric CO_2 concentrations and whether elevations in both atmospheric CO_2 and air temperature are consistent from year to year are less well known. Our aim was to record atmospheric CO_2 concentrations, air temperature and other environmental variables in an urban area and compare it to suburban and rural sites to see if urban sites are experiencing climates expected globally in the future with climate change. A transect was established from Baltimore city center (Urban site), to the outer suburbs of Baltimore (suburban site) and out to an organic farm (rural site). At each site a weather station was set-up to monitor environmental variables annually for five years. Atmospheric CO_2 was significantly increased on average by 66 ppm from the rural to the urban site over the five years of the study. Air temperature was significantly higher at the urban site (14.8 ºC) compared to the suburban (13.6 ºC) and rural (12.7 ºC) sites. Relative humidity was not different between sites but vapor pressure deficit (VPD) was significantly higher at the urban site compared to the suburban and rural sites. During wet years relative humidity was significantly increased and VPD significantly reduced. Increased nitrogen deposition at the rural site (2.1 % compared to 1.8 and 1.2 % at the suburban and urban sites) was small enough not to affect soil nitrogen content. Dense urban areas with large populations and high vehicular traffic have significantly different microclimates compared to outlying suburban and rural areas. The increases in atmospheric CO_2 and air temperature are similar to changes predicted in the short term with global climate change,

therefore providing an environment suitable for studying future effects of climate change on terrestrial ecosystems.

Introduction

The conversion of rural lands into urban areas with high traffic volumes and dense residential and commercial buildings greatly affects the local air quality and energy balance. Cities are large consumers of fossil fuels, because as in the US and other countries, the majority of the population resides in urban areas (United Nations, 2004). This results in urban areas being responsible for the largest proportion of anthropogenic emissions such as CO_2 and nitrous oxides (Pataki et al., 2006). Human and vehicle activity has been found to contribute more than 80 % of the atmospheric CO_2 in urban areas (Koerner and Klopatek, 2002). Also, the conversion of natural land into roads and buildings changes the albedo and heat capacity of an area resulting in urban areas being significantly warmer than if it remained as a rural landscape (Oke, 1982). If urban environments are elevated in atmospheric CO_2 and temperature for sustained periods this could provide a suitable system for studying the effects of future global climate change on plant population and community dynamics with out the high cost of equipment and other resources currently needed to carry out such studies.

The elevation of air temperatures in city centers compared to less built-up areas is a phenomenon that has been recorded since1833 (Oke, 1982). The greatest warming has been found at night as concrete, stone and other materials used in building construction have a high thermal conductivity, meaning they can quickly absorb heat energy from radiation during the day and this is slowly released at night. Heat released directly from building ventilation and vehicular traffic also contribute to city heating and can vary annually and diurnally. The degree of heating within a city is very variable and is unique to each city based on its location, building layout and traffic (Oke and Maxwell, 1975). A city wide examination of temperature in Baltimore, U.S.A. found that minimum temperatures are closely related to population and the difference between urban and rural minimum temperatures has been increasing as population increases (Brazel, 2000). The densely built-up areas in the center of Baltimore are 5-10 ºC warmer than residential or forested and agricultural areas (Brazel, 2000), making it a good model to study climate differences between urban centers and adjacent rural areas.

Near-surface CO_2 concentrations have been documented in several cities across the world (Canada, Kuwait, Mexico, Switzerland, UK, USA) to evaluate the dynamics of atmospheric CO_2 over short periods of time (Berry and Colls, 1990; Reid and Steyn, 1997; Idso et al., 2001; Nasrallah et al., 2003; Velasco et al., 2005; Vogt et al., 2006). The majority of these studies analyzed daily and diurnal fluctuations in CO_2 concentrations and concluded that the major source of CO_2 is from vehicular traffic as peak CO_2 concentrations correlate to high traffic volume during workdays and is significantly reduced at weekends (Idso et al., 1998, Idso et al. 2001; Idso et al., 2002; Nasrallah et al., 2003; Velasco et al., 2005). In Nottingham, U.K. an 8 month study found a small difference in CO_2 concentration of only 5 ppm between a rural location and an urban city site (Berry and Colls, 1990). Although the small difference between sites and large variability in CO_2 concentrations are likely related to the close proximity of power stations to both sites which were only 15 km apart (Berry and Colls, 1990). In Phoenix, U.S.A. CO_2 concentration was monitored for nearly a year and values ranged from a daily minimum of 390 ppm rising to a daily maximum of 491 ppm, although a maximum value of 619 ppm was attained (Idso et al., 2002). Over a two week period CO_2 concentration varied significantly from day to day with the highest peak of 650 ppm which was 76% higher than the low of 369 ppm (Idso et al., 2001). Whereas Day et al. (2002) found the urban area was elevated by 19 ppm compared to a suburban area, but their study area was a distance from major streets and less influenced by vehicle emissions. Few studies have concurrently compared urban to rural CO_2 concentrations to determine the amount CO_2 concentrations are elevated by urbanization and whether any increases are sustained and consistent from year to year.

Large urban areas are affecting the microclimate, but few studies have recorded these changes for any length of time to ensure the consistency of data and suitability for investigating effects on plant biological systems and monitored other global climate change variables concurrently. The aim of this study was to investigate whether a high population city center has a climate similar to that predicted in the short term (50-100 years) with global climate change. Baltimore was selected as it is one of the largest cities in the U.S.A. with dense residential and commercial buildings and high traffic volumes in the city center. The outskirts of Baltimore become more suburban with green areas on the outskirts of the city and becoming rural dominated by agricultural land. This location is ideal for comparing microclimate changes from an urban city center transitioning to a more suburban and rural areas. The objectives of this study were to characterize the microenvironment associated with an urban location relative to a suburban and rural location. A secondary objective was to compare the microenvironmental characteristics to climatic conditions predicted with global climate change.

Methods

Site description

A transect was established running east west from downtown Baltimore city to a rural agricultural area in western Maryland. Three sites were selected along the urban-rural gradient: an organic farm near Buckeystown, Maryland (39º18’N 77º26’W, elevation 109.8 m) approximately 87 km west of Baltimore (rural site), a nature center approximately 11 km west of Baltimore (39º18’N 76º41’W, elevation 98.9 m) on the outer edge of the city (suburban site), and Baltimore city center (39º16’N 76º36’W, elevation 6.8 m; urban site). Each site is surrounded by grass which is mowed frequently through the growing season. The urban site is surrounded by large commercial and residential buildings and is very close to the harbor which contains a large body of water within the city center. The suburban site is surrounded by trees as it is part of the Carrie Murray nature center within the Gywnn Falls Park. The park area is approximately 480 ha and is surrounded by housing and lawns. The rural site is located on an organic farm which predominantly grows alfalfa and orchard grass for animal fed. The area is dominated by agricultural land mainly for grazing with a few residences scattered across the landscape. Detailed description of site selection and set-up are described in Ziska et al. (2003, 2004).

Site microenvironmental measurements

At each site a weather station was established that monitored the following variables every 15 minutes using a CR10X data logger (Campbell Scientific, USA): air temperature and relative humidity (Vaisala, Finland), atmospheric CO_2 concentration (Quibit, Canada), soil temperature (Campbell Scientific, USA) and moisture (Decagon Devices, USA; 10 cm depth), wind speed and direction (R. M. Young Company, USA), Photosynthetic Photon Flux Density (quantum sensor; LI-COR, USA) and total and diffuse radiation (pyranometer; Delta-T Devices, UK) and precipitation (Tipping bucket rain gage; Texas Instruments, USA). Atmospheric CO_2, air temperature, wind speed and direction and radiation variables were measured 1.5-2.0 m off the ground. Tipping rain buckets for precipitation were located approximately 1 m off the ground. Additionally tropospheric ozone was monitored periodically through the summer months of 2003-2005 using chemically sensitive filter paper. Wet deposition of nitrate and nitrite in rain water and dry deposition of nitrate were monitored throughout the year of 2005. Soil nitrogen content was measured at the start of the growing season to estimate the input of nitrogen to a site from deposition. To remove variability associated with water availability, evaporation at each site was monitored through the growing season and any moisture deficit at a site compared to the others was eliminated by additional watering.

Statistics

Atmospheric CO_2 was examined to see if there were diurnal differences between sites and years using analysis of covariance. The covariate was time of day and the independent factors were site and year. Air temperature, soil temperature, precipitation, RH and VPD were also analyzed using analysis of covariance but the covariate was day of year. Differences in ozone and soil nitrogen content between sites were analyzed using analysis of variance. Data were transformed where appropriate to meet the assumptions of normality and equality of variances for ANOVA. Total and diffuse radiation at the urban and rural sites was analyzed using the nonparametric Mann-Whitney U test as the data were not normally distributed. The variance of soil moisture variables was not equal so the nonparametric Kruskall Wallis test was performed. All statistics were performed using Statview (SAS Institute, USA).

Results

Atmospheric CO_2

Atmospheric CO_2 concentration was significantly different between the three sites ($P >$ 0.01; Fig. 1). The highest concentration was at the urban site (488 ppm) the lowest at the rural site (422 ppm) and the suburban site intermediate to the other two sites (442 ppm). CO_2 concentration also differed significantly between years ($P = 0.01$), although the average range in CO_2 concentrations between years was small 443-459 ppm. Time of day also significantly affected CO_2 concentration ($P > 0.01$) with the lowest CO_2 concentration in the early afternoon and peaking in the early hours of the morning (Fig. 1). There was no difference between CO_2 concentrations at the weekend (448.6 ppm) compared to the weekday (448.7 ppm) at all sites.

Air and soil temperature

Daily air temperature differed significantly between the sites (P = 0.01; Fig. 2) with the highest air temperature at the urban site (14.8 ºC), the lowest at the rural site (12.7 ºC) and the suburban site falling in between the two extremes (13.6 ºC). Daily air temperature was also significantly different between years (P < 0.01) with the highest average temperature in 2006 (14.3 ºC) and the lowest in 2003 (13.2 ºC). The same significant differences were apparent when temperature was calculated for night time and day time (P < 0.01; Fig. 2). The temperature differences at night time were: urban (13.1 ºC), suburban (10.9 ºC) and rural (10.4 ºC) and at day time: urban (16.5 ºC), suburban (16.2 ºC) and rural (14.8 ºC). The biggest difference in temperature occurring at night between urban and rural sites (2.3 ºC). Although these differences in temperature between sites are small, compared to the annual variation in temperature, they are consistent through out the year (Fig. 2.). The increase in air temperature at the urban site resulted in the growing season being longer compared to the suburban and rural sites. On average the growing season was 258 days at the urban site and 215 and 210 days respectively at the suburban and rural sites (Table 2).

Soil temperature (10 cm depth) was significantly different between sites (P < 0.01; Fig. 3). The highest temperature was at the urban site (14.8 ºC) and the lowest at the rural site (14.1 ºC). The greatest difference in soil temperature was between the urban and rural sites (0.7 ºC) and the urban and suburban sites (0.5 ºC) there was no significant difference in soil temperature between the rural and suburban site (0.1 ºC). The major difference between sites occurred in the last four months of the year (Fig. 3) as the urban site remained warmer longer while temperatures dropped quicker at the other two sites.

Moisture variables

Precipitation was not significantly different between sites ($P = 0.17$) or between years ($P = 0.54$), although there was considerable variation in precipitation over the five years of the study (Table 1). The highest precipitation was in 2003 (1196 mm) which was also the wettest year on record for the state of Maryland. This resulted in relative humidity being significantly greater ($P < 0.01$) and vapor pressure deficit (VPD) to be significantly reduced ($P < 0.01$) in 2003 compared to the other years (Table 1). Relative humidity was not significantly different between sites ($P = 0.12$) but VPD was significantly greater at the urban site ($P < 0.01$) as air temperature was also higher.

Soil moisture was significantly different between site and year. The wettest site on average was the urban site this was because soil moisture in 2004 at this site was higher than previous years (Table 1). This may have been because of additional watering to meet evaporative demand. Apart from the high soil moisture at the urban site in 2004 all other sites and years had very similar average soil moisture.

Solar radiation

Total and diffuse radiation was measured at the urban and rural sites during 2005 and 2006 (data no shown). On a daily basis there was no significant difference between total radiation ($P = 0.08$) at the urban (average 347.9 μmol m^{-2} s^{-1}) and rural (average 398.5

μmol m^{-2} s^{-1}) sites. Diffuse radiation although more than 50 % lower than total radiation, was not significantly different (P = 0.19) between the urban (average 159.2 μmol m^{-2} s^{-1}) and rural (average 189.3 μmol m^{-2} s^{-1}) sites.

Ozone and nitrogen deposition

Ozone concentrations did not change significantly between the sites along the transect (P = 0.25; Fig. 4). On average the ozone concentration for 2005 was 44 ppb ± 22 (one standard deviation) and was not high enough to affect plant physiology and growth. Ozone was also measured for short time periods in 2003 (day 248-273 September) and 2004 (day 78- 174 March-June) and the average ozone concentrations respectively were 24 ppb and 34 ppb, which during these time periods corresponds to the 2005 data.

Wet and dry deposition was highest at the rural and lowest at the urban site (Table 3). Soil total nitrogen content was not significantly different between sites (P= 0.59). The addition of wet and dry deposition to soil contributed only 2.1, 1.8 and 1.2 % nitrogen annually to the rural, suburban and urban sites respectively.

Discussion

Across the transect atmospheric CO_2 and temperature were elevated at the urban site and gradually reduced out to the suburban and rural sites. This is consistent with other studies that have found air temperature and atmospheric CO_2 are closely related to population and associated high traffic volume in urban city centers (Idso et al., 1998, Brazel, 2000, Idso et al. 2001; Idso et al., 2002; Nasrallah et al., 2003; Velasco et al., 2005). Increased air temperature at the urban site significantly increased vapor pressure deficit (VPD). While during years of above normal precipitation relative humidity was significantly increased and VPD significantly reduced. Nitrogen deposition although highest at the rural site was not great enough to increase soil nitrogen content compared to the other sites. The changes in the microclimate and deposition of nutrients along the transect are consistent with predictions of modifications in the environment expected with global climate change. It appears that densely populated urban areas could provide a setting that is suitable for studying the effects of future global climate change on terrestrial ecosystems.

Globally averaged surface atmospheric CO_2 concentrations are 381 ppm (2006; http://www.cmdl.noaa.gov/ccgg/trends/) and the most conservative estimate is an increase to 159 ppm by 2100 (IPCC, 2001). Along the transect on average the lowest CO_2 concentration was at the rural site, 422 ppm, which increased by 66 ppm at the urban site. This difference in CO_2 concentration between sites was maintained over the five year period with the average annual CO_2 concentration at the rural site ranging from 395-439 ppm and the urban site 448-537 ppm. This difference between the urban and rural sites is similar to the increase in CO_2 concentration found in Phoenix, U.S.A., where an increase of 111-185 ppm was reported from a pristine rural site to the city center (Idso et al., 1998 and 2001). The sustained increase in CO_2 concentration over five years between an urban and rural site, although not as large as expected with global climate change, is a significant increase that will impact biological systems.

Air temperature globally varies greatly but on average it is predicted to increase by 1.4-5.8 ^{o}C by 2100 and this increase will be greatest on land in the northern hemisphere and at night (IPCC, 2001). Along the transect temperature was significantly different between sites with the greatest difference at night between the urban and rural sites (2.8 ^{o}C). This difference was greatest in September and is likely a consequence of buildings and other manmade structures absorbing heat energy through the summer months and gradually cooling off through the winter. This resulted in the growing season at the urban site being 36-70 days longer over five years than the other two sites as freezing temperatures didn't occur until later in the year. Soil temperature was also higher by 0.7 ^{o}C at the urban compared to the rural site. The soil temperature difference between the sites was highest in the last four months of the year, similar to air temperature patterns. Measurements of solar radiation at the urban and rural sites indicated that there were no differences between the sites and temperature was not influenced by shading from buildings at the urban site. Air temperature was consistently higher at the urban site and similar to predictions of global climate change resulted in fewer frost days and warmer night time temperatures.

Precipitation was above average in Maryland for four of the five years of the study and 2003 was the wettest year recorded over more than 100 years (http://www.noaa.org/climate.html). Although precipitation measured in our study was not significantly different between sites and years there is a great amount of variation across the region and between years (Table 1). Global climate change models predict in the future precipitation will increase, particularly in the Northern Hemisphere, and there will be an increase in heavy precipitation events (IPCC, 2001). Urban areas are unlikely to influence regional events such as precipitation, although it appears that the State of Maryland as a whole is seeing more extreme and higher annual precipitation than experienced in the last 100 years. One consequence of urbanization on moisture variables is increased air temperature at the urban site significantly increased VPD. Whereas, during wet years relative humidity was significantly increased and VPD significantly reduced. VPD directly affects plant physiology (Aphalo and Jarvis, 1991), influencing gas exchange and growth rates of plants.

Urban environments can impact air quality variables other than atmospheric CO_2 such as tropospheric ozone and nitrogen deposition. In 2006 Baltimore experienced 17 days where ozone levels on average were above 100 ppb for 8 hours and western Maryland experienced 2 days (considered unhealthy for sensitive groups; http://www.mde.state.md.us/Programs/), all occurring between May and August. Our measurements at each site indicated peak values between June and September but on average across the year ozone concentration was below levels that would affect human or plant physiology (McKee, 1994). Wet and dry deposition added a small percent of nitrogen compared to soil nitrogen content. Nitrogen deposition appeared to be highest at the rural site compared to the urban although soil nitrogen values were not different between sites. It is evident that urban environments provide a microclimate that is representative of changes predicted in the future with global climate change, consequently vegetation within urban areas are currently experiencing elevated atmospheric CO_2 and temperature levels that can significantly affect plant growth compared to rural areas.

Over the five year period of this study it appears that a dense population, urban center, is affecting the microclimate so that it is similar to climate predicted globally in the next 100 years. Over the five years of the study CO_2 concentrations and air temperature were consistently higher at the urban site compared to the suburban and rural sites. In the U.S.A. 80 % of the population resides in urban areas and urbanization is continuing to increase (United Nations, 2004). Increasing land use change from rural agricultural areas to dense populated urban areas will have significant impacts on carbon emissions and cycling (Imhoff et al., 2004).

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Table 1. Moisture variables from each site across the transect. Precipitation is summed over the year. RH, VPD and soil moisture are a daily average over the year. Average is the over all five years and the values in brackets are the daily standard deviations. Soil moisture was not recorded in 2002 and 2003.

Variable	***Site***	***2002***	***2003***	***2004***	***2005***	***2006***	***Average***
Precipitation (mm)	Rural	1484	1288	906	978	767	1112 (4)
	Suburban	778	1150	970	1065	1052	1027 (4)
	Urban	785	1151	818	679	809	867 (3)
RH (%)	Rural	61.5 (20.7)	77.1 (14.9)	72.9 (15.2)	70.9 (13.9)	69.1 (14.5)	70.3 (8.9)
	Suburban	63.8 (18.1)	78.6 (16.1)	69.5 (15.7)	68.6 (14.2)	68.1 (15.9)	68.9 (10.2)
	Urban	60.2 (15.6)	68.4 (15.8)	66.3 (15.5)	64.9 (15.8)	60.7 (16.1)	64.1 (7.5)
VPD (kPa)	Rural	0.62 (0.38)	0.35 (0.25)	0.42 (0.26)	0.47 (0.31)	0.50 (0.30)	0.47 (0.20)
	Suburban	0.60 (0.38)	0.37 (0.26)	0.48 (0.28)	0.52 (0.32)	0.55 (0.35)	0.51 (0.22)
	Urban	0.72 (0.47)	0.54 (0.38)	0.59 (0.36)	0.67 (0.46)	0.72 (0.46)	0.65 (0.33)
Soil moisture (%)	Rural			13.8 (1.8)	10.1 (5.3)	9.7 (4.7)	12.0 (3.4)
	Suburban			10.1 (1.4)	9.3 (3.0)	12.5 (2.3)	10.8 (1.6)
	Urban			19.3 (2.2)	8.7 (3.9)	12.7 (3.5)	14.4 (2.7)

Table 2. Growing season length in days at each site over five years based on the last day that a frost occurred after winter and the first day that a frost appeared before winter.

	Rural			Suburban			Urban		
Year	***Last frost day***	***First frost day***	***Growing season length***	***Last frost day***	***First frost day***	***Growing season length***	***Last frost day***	***First frost day***	***Growing season length***
2002	April 4th	November 2nd	213	April 8th	November 1st	208	March 24th	November 27th	249
2003	March 16th	October 23rd	222	April 2nd	October 23rd	205	March 15th	December 2nd	263
2004	April 8th	November 10th	217	April 8th	November 10th	217	March 25th	December 18th	269
2005	April 16th	November 11th	210	March 22nd	November 17th	241	March 15th	November 18th	249
2006	April 9th	October 15th	190	March 23rd	October 13th	205	March 21st	December 5th	260

Table 3. Dry and wet deposition nitrogen measured in 2005 at each site and compared to US-EPA data (http://cfpub.epa.gov/gdm/index.cfm). Soil nitrogen content was quantified at each site and addition from total wet and dry deposition was estimated. Total wet deposition is nitrate and nitrite summed from each site and ammonium estimated as 38% of nitrate based on US-EPA values. Total dry deposition is estimated as 52 % of wet deposition based on US-EPA data (http://cfpub.epa.gov/gdm/index.cfm).

	Rural	**Suburban**	**Urban**	**US-EPA, Beltsville, MD**
Dry deposition (μg m^{-3})				
Nitric acid	6.19	3.09	5.24	2.04
Nitrate				1.33
Ammonium				1.43
Wet deposition (Kg ha^{-1})				
Nitrate	7.72	6.28	4.47	2.82
Nitrite	0.19	0.12	0.08	
Ammonium				1.76
Soil N (Kg ha^{-1})	771.8	735.8	783.9	
Total wet deposition (Kg ha^{-1})	10.84	8.78	6.24	
Total dry deposition (Kg ha^{-1})	5.64	4.57	3.24	

Figures

Figure 1. Near surface atmospheric CO2 concentration averaged over a 24 hour period for each site along the transect for the five years of the study. Data were recorded every 15 minutes resulting in 96 values over a 24 hour period consequently data points and error bars are not included but the data are connected by straight lines. The error bars shown in each graph is the maximum standard deviation from all sites.

Figure 2. Daily (24 hours), daytime and nighttime air temperature for each site along the transect averaged over the five years of the study. The error bars for the graphs on the left side are the maximum standard deviation. The graphs on the left represent the deviations in temperature between sites, the error bars are one standard deviation.

Figure 3. Annual soil temperature (10 cm depth) averaged over the five years of the study and differences between sites on a monthly basis. The error bars are one standard deviation.

Figure 4. Tropospheric ozone measured at each site through the growing season of 2005. The error bars are one standard deviation.

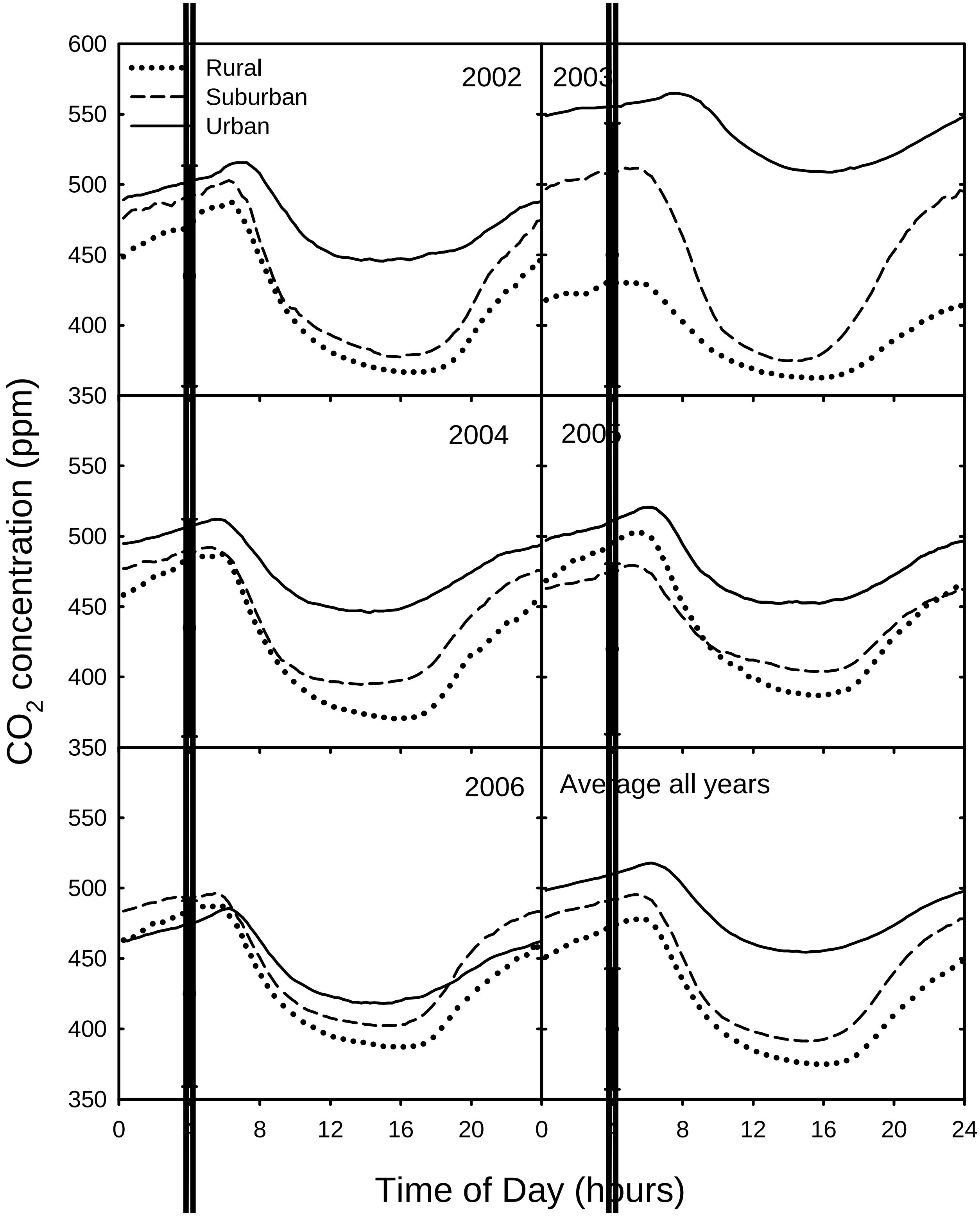

Figure 1. George et al.

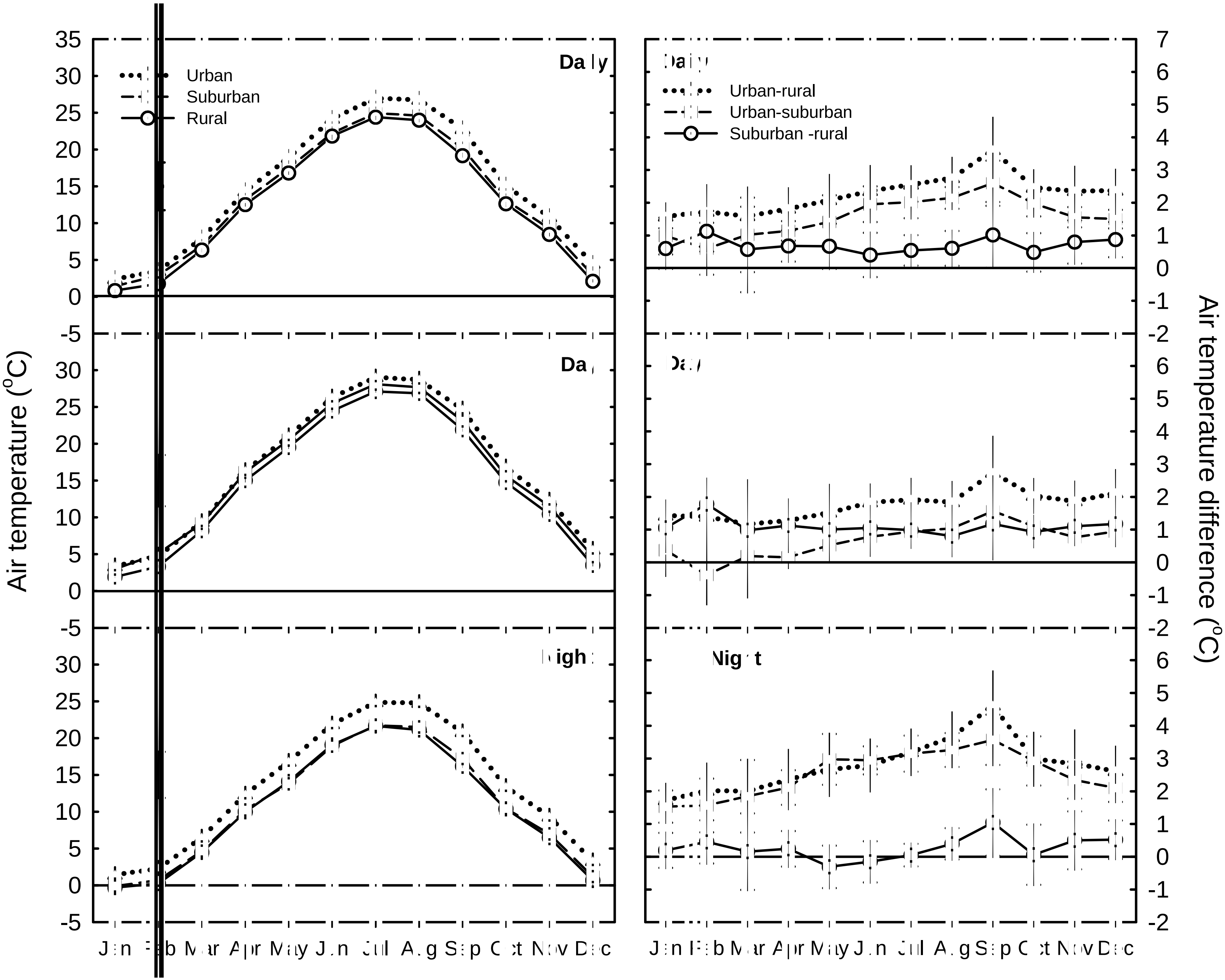

Figure 2. George et al.

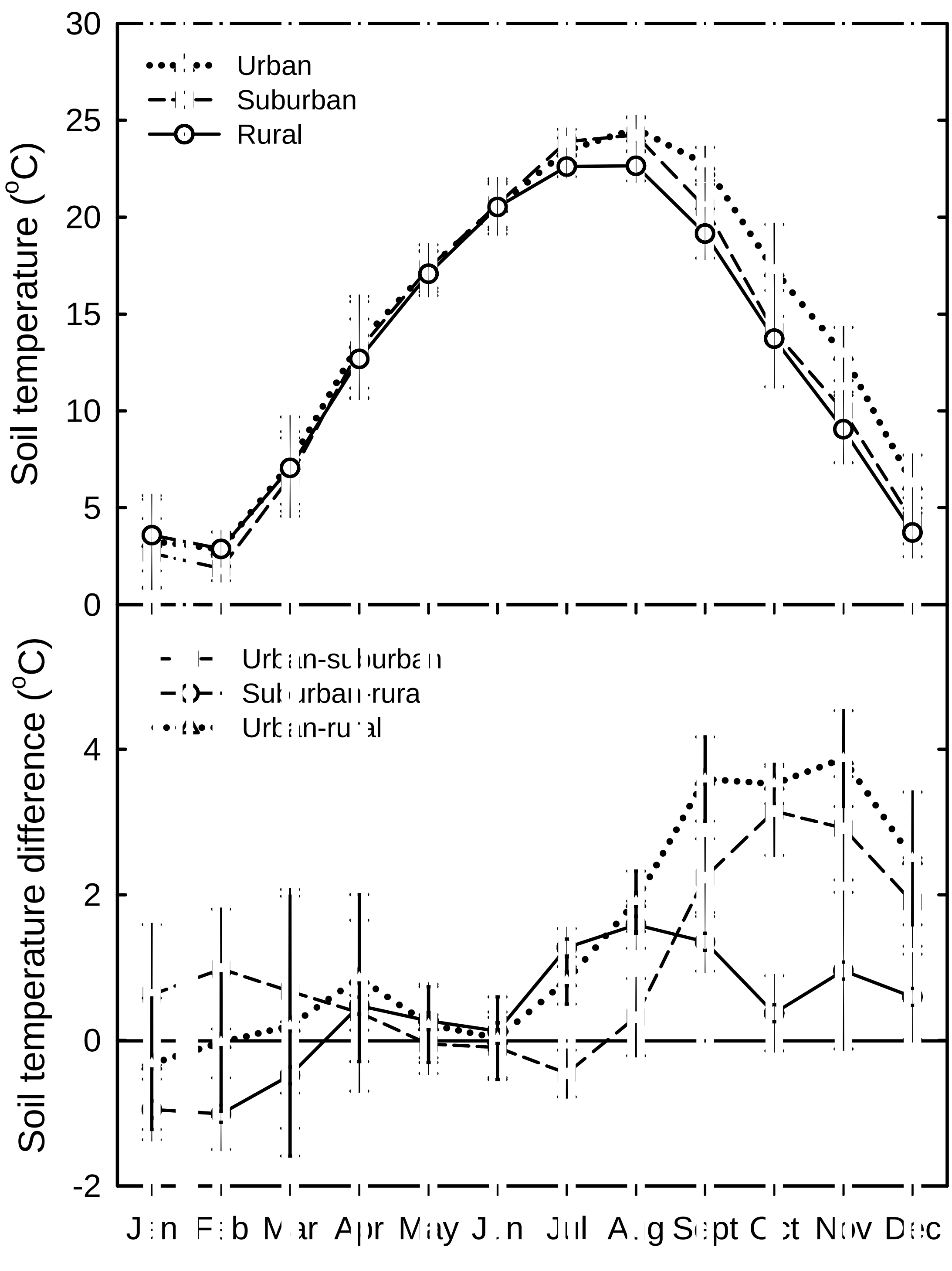

Figure 3. George et al.

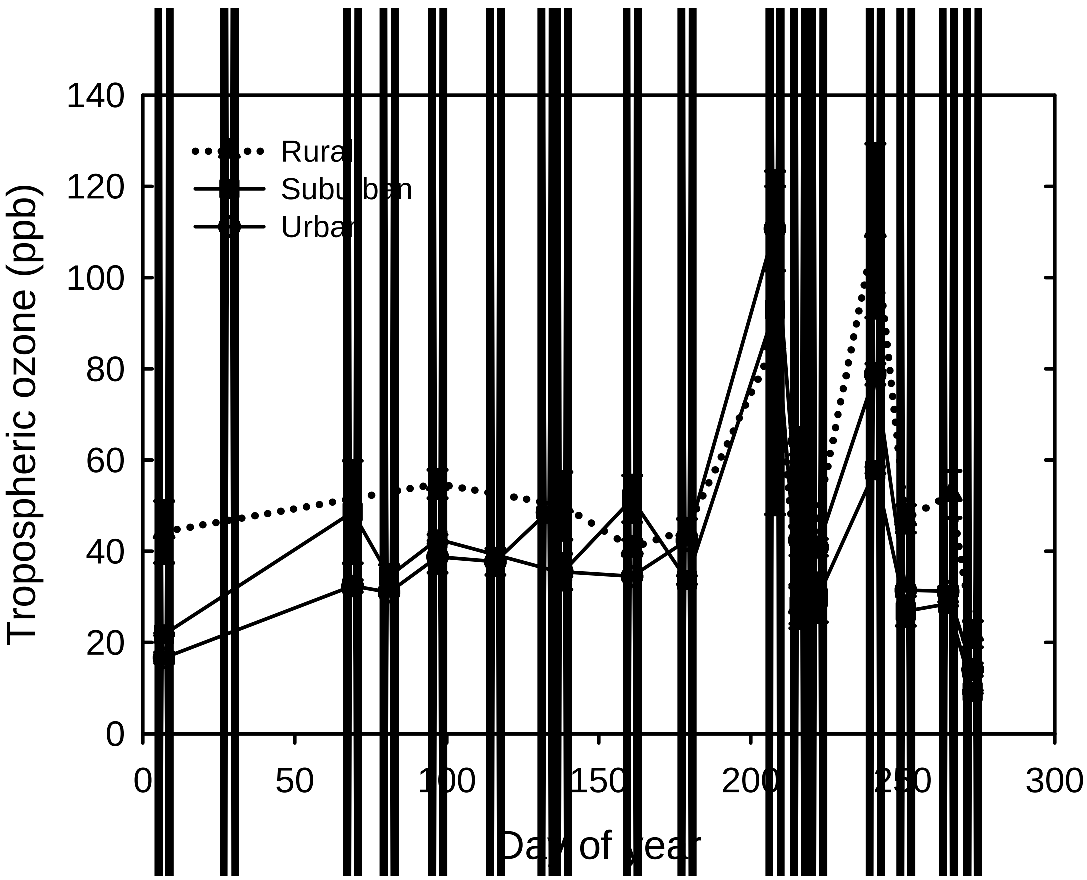

Figure 4. George et al.