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Characterization of an urban-rural CO₂/temperature gradient and associated changes in initial plant productivity during secondary succession

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Abstract To examine the impact of climate change on vegetative productivity, we exposed fallow agricultural soil to an in situ temperature and CO₂ gradient between urban, suburban and rural areas in 2002. Along the gradient, average daytime CO₂ concentration increased by 21% and maximum (daytime) and minimum (nighttime) daily temperatures increased by 1.6 and 3.3°C, respectively in an urban relative to a rural location. Consistent location differences in soil temperature were also ascertained. No other consistent differences in meteorological variables (e.g. wind speed, humidity, PAR, tropospheric ozone) as a function of urbanization were documented. The urban-induced environmental changes that were observed were consistent with most short-term (~50 year) global change scenarios regarding CO₂ concentration and air temperature. Productivity, determined as final above-ground biomass, and maximum plant height were positively affected by daytime and soil temperatures as well as enhanced [CO₂], increasing 60 and 115% for the suburban and urban sites, respectively, relative to the rural site. While long-term data are needed, these initial results suggest that urban environments may act as a reasonable surrogate for investigating future climatic change in vegetative communities.

Keywords Climate change · Lambsquarters · Urbanization

Introduction

Presently, plants with C₃ type photosynthesis (i.e. 96% of all plant species) are carbon limited; consequently, increases in global atmospheric [CO₂] stimulate photo-

synthesis and subsequent growth. This has been observed in numerous experiments that have evaluated the growth and reproductive response of individual plant species (e.g. Cure and Acock 1986; Kimball et al. 1993; LaDeau and Clark 2001).

While important, these data have unclear implications regarding responses of plant communities or ecosystems since they do not address plant assemblages, nor do they include other climatic variables such as temperature (DeLucia et al. 1999; Reich et al. 2001). Yet, in typical climate change scenarios, both ambient air temperature and [CO₂] increase concomitantly since elevated CO₂ is a primary driver of climate change (Intergovernmental Panel on Climate Change (IPCC) scenarios IS 92e and IS 92a in Schimel et al. 1996). Although model projections have been used to interpolate multi-factor climatic changes (Schimel et al. 1996), the complexity of projected ecosystem changes, particularly as they relate to scale, make such analyses incomplete. In many instances this is a result of the paucity of data regarding the response of plant communities to simultaneous increases in [CO₂] and temperature.

In the current study we quantify meteorological variables and characterize an existing carbon dioxide and temperature gradient along a rural-urban transect. Our goal was to determine if such a gradient simulated short-term (~50 year) climate projections regarding atmospheric CO₂ and air temperature and to quantify associated changes in vegetative productivity associated with first year re-growth from fallow farmland. The results reported here are part of a longer-term (3–5 year) effort to quantify changes in species diversity and productivity during secondary succession as a function of urbanization.

Materials and methods

Three sites had been selected along a CO₂/temperature transect which had been used in a previous study and where the microclimate had been partially characterized (Ziska et al. 2003). These sites are located at an organic farm near Buckeystown, Maryland (rural,

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control site) approximately 50 km from the center of the city of Baltimore; a city park (Carrie Murray Nature Center, suburban site) which is on the edge of the city/county line, approximately 10 km from the city center and a site at the Baltimore Science Center (urban site) which is <0.5 km from the city center. All sites are surrounded by mowed grass, or an alfalfa/orchard grass mixture (organic farm) which is periodically harvested.

Beginning in late February 2002, the top 20 cm of first year fallow soil (with its viable seed bank) was removed from the Beltsville experimental farm over a 6×9 m area. The soil had not received any pesticide applications for at least 5 years. Soil was bulked, then sieved to remove rhizomes, stolons and corms. This was done to ensure that only seed was contained within the soil and that regrowth from below ground structures did not confound germination and emergence from the seed bank. Following bulking, the soil was mixed uniformly and subsamples of the soil were placed in 20×30 cm flats in sunlit greenhouses to evaluate the seed bank. Germination from these subsamples indicated uniform mixing and the presence of approximately 30 species including annual and perennial, broadleaved species and grasses. Remaining soil within the 6×9 m area (primarily B and C horizons, from 20 to 110 cm) was then evacuated by backhoe, mixed and set aside. For each site along the transect described above, four 2×2 m plots were excavated to a depth of ~1.1 m with the soil removed. The lower horizons (i.e. the soil obtained from the Beltsville site from 20 to 110 cm) were added to each plot and tamped to obtain a uniform bulk density. Following placement of the lower layers, the seed bank soil was added to the top 20 cm of each plot. Soil samples were then taken at each site to a depth of 30 cm and analyzed at the University of Maryland Soil Testing Laboratory at College Park, Maryland. Soil data indicated characterized the soil as a *Cordurus* silt-loam (*Cordurus hatboro*) with pH 5.5, an average organic matter of 2.2% and excessive amounts of N, P and K with no micro or macro nutrient deficiencies. No differences in soil characteristics were observed as a function of location. All plots were randomly placed at a given location and were not shaded by surrounding structures. To minimize border effects, shade cloth which has been specially designed to simulate leaf spectral properties (EZ Gardener, Waco, Tex.) was placed around each plot, and raised to canopy height as the plants grew.

Weather stations (Campbell Scientific, Logan, Utah), were installed at all sites along the transect. A boxed enclosure (ENC) containing a datalogger (CR10x) was mounted on a tripod (CM6) and connected to an anemometer (03001), an air temperature and humidity probe (CS500), a soil temperature probe (CS 107) at a depth of 15 cm, a six plate radiation shield (41301 RM), a rain gauge (TE 525), an infrared CO₂ analyzer (S151, Qubit Systems, Ontario, Canada) and a quantum sensor (LI190SB, Li-Cor, Lincoln, Neb.). In addition, a US weather bureau (USWB), class A evaporation pan was placed at each site. Each weather station was powered by a 12-V direct current deep-cycle marine battery that was recharged by a 10-W solar panel (MSX10R, Campbell). All environmental parameters were recorded at 5-min intervals and downloaded weekly through use of a storage module (SM192, Campbell) and keypad (CR10KD, Campbell). All instruments were factory calibrated. CO₂ analyzers were re-calibrated monthly for each site. Plots at each site were hand-watered as needed to match estimates of evapo-transpiration as determined from meteorological

values and pan evaporation. Nitrate (NO₃) and nitrite (NO₂) rainwater content was measured in 2002 via ultraviolet spectroscopy following high performance liquid chromatography to achieve separation (NO₃) and colorimetry with sulfanilamide (NO₂), respectively, in order to quantify nitrogen deposition along the transect.

Plots at each site along the transect were not harvested until the occurrence of frost at each site and subsequent mortality of the plot. This occurred on November 25, November 26 and December 17 giving a growing season of 210, 211 and 231 days for the rural, suburban and urban sites, respectively. Following the occurrence of freezing temperatures, height was determined on 12 of the lambsquarters plants from each plot (the dominant species), and all above ground biomass was cut at ground level and removed. Biomass was dried until a constant dry weight was obtained, then weighed. Four plots at each site served as replicates for that transect location.

Results and discussion.

Both [CO₂] and ambient air temperature were enhanced by the level of urbanization. Seasonally, urbanization consistently increased the average daytime [CO₂] by ~21% relative to the rural, farm site (Table 1). Dividing cumulative degree days (beginning at DOY 73, after minimum temperatures exceeded 0°C) by the total number of days within the growing season (i.e. until initial frosts) gave increases of 1.3 and 1.6°C in daily maximum temperatures for the suburban and urban sites respectively, relative to the rural site (Table 1). Interestingly, although no differences in maximum air temperature were observed between suburban and urban locations, minimum night-time temperatures were significantly higher for the urban site (Table 1). Soil temperature for the first 30 days of the experiment was also significantly higher for both the suburban and urban sites (Table 1). In addition, the first fall frost was delayed for the suburban and urban sites by 1 and 21 days respectively, giving a longer frost-free season.

Overall, it is clear that the two principle environmental parameters expected to increase with climate change, ambient air temperature and [CO₂], also increase in response to urbanization. The observed increases noted here are consistent with most climate change scenarios (e.g. greater night-time than daytime temperature, longer growing season, more CO₂) (Kukla and Karl 1993; Schimel et al. 1996) and consistent with the short-term (~50 year) projections for [CO₂] and temperature made by the Intergovernmental Panel on Climate Change (IPCC)

Table 1 Seasonal changes in micro-meteorological characteristics along the urban transect for 2002. CO₂ is average weekly daytime concentration. *D* and *N Temp* are average daily maximum (day-time) and minimum (night-time) air temperature, *S Temp* is soil temperature averaged for the first 30 days of the experiment (i.e. the first 30

days following the last spring frost). Different letters within a column indicate significant differences between sites as determined by Fisher's protected least significant difference test ($P < 0.05$). *RH* relative humidity, *PAR* photosynthetically active radiation (i.e. radiation between 400 and 700 nm), *WS* wind speed

Micro-climate characterized along the transect

Site	CO ₂ (μmol mol ⁻¹)	D Temp (°C)	N Temp (°C)	S Temp (°C)	VPD (KPa)	PAR (μmol m ² s ⁻¹)	WS (m s ⁻¹)
Rural	385 b	24.6 b	12.9 b	4.3 c	0.77	315	2.2 a
Suburban	401 b	25.9 a	13.1 b	5.1 b	0.79	322	0.5 b
Urban	466 a	26.2 a	16.3 b	6.3 a	1.03	285	1.9 a

Table 2 Seasonal changes in air quality characteristics along the urban transect for 2002. O₃ levels reported as 8 h averages from May through September determined at US Environmental Protection Agency (EPA) monitoring sites in the western part of Maryland (Frederick County) and in Baltimore City. These sites correspond approximately to the rural and urban transect sites. Note that sulfur dioxide (SO₂) values did not exceed EPA standards for any part of the state (for a complete description of sites and air quality values, see <http://www.Epa.gov/air/oaqps/cleanair.html>).

Monthly 8-h tropospheric ozone averages (nl O ₃ l ⁻¹ air)					
	May	June	July	August	Sept
Rural	28.2	56.4	53.3	53.3	41.7
Urban	28.1	51.7	46.6	48.3	33.3
Difference	0.1	4.6	6.7	5.0	8.5

(McCarthy et al. 2001). However, while [CO₂] and temperature increased along the transect, what other micro-meteorological variables were changing, and could these changes also impact biomass productivity?

As expected, urban and rural ozone values were high relative to accepted standards of the US Environmental Protection Agency (<http://www.epa.gov/air/oaqps/cleanair.html>). However, daily (8 h) ozone averaged from May through September, while slightly higher for the rural site, did not differ significantly from the urban location (Table 2). In addition, no difference in 1 h peak values was observed between locations (data not shown). The overall average observed here and the small difference in daily averages (approximately 5 nl O₃ l⁻¹ air) are less than that hypothesized to induce any change in growth or biomass for plant species in general (e.g. Fig. 3, Krupa and Kickert 1997). Although specific data on weed sensitivity to tropospheric ozone remain scarce, data for *Setaria faberi* and *Ambrosia artemisiifolia* (foxtail and ragweed, two species found along the transect locations) indicated no biomass or growth response to continuous ozone exposures of 110 and 64 nl O₃ l⁻¹ air, respectively, relative to a filtered (i.e. <20 nl O₃ l⁻¹ air) control (Endress et al. 1999; Ziska 2002). Cultivated sunflower has shown reductions in photosynthesis with ozone (DiCagno et al. 2001), but at much higher levels (160 nl O₃ l⁻¹ air) than seen in the current study. Overall, while tropospheric ozone levels were higher than might be encountered in growth chamber conditions, the lack of any ozone gradient between sites, and the low number of high (i.e. “Code-red”) ozone days (approximately 10 over a 6 month period), argue against it being a significant confounding factor. It is possible that the prevailing ozone concentration increased the responsiveness to elevated [CO₂] (Volin et al. 1998). However, the ozone levels reported here are representative of large areas of eastern North America (Krupa and Manning 1988; Krupa and Kickert 1997).

Were there observed changes in water quantity or quality as a function of transect location? ET was slightly higher for the rural site, as was precipitation. However, additional irrigation from tap water (i.e. no added nutrients) met and was slightly over that estimated from seasonal ET (Table 3).

Table 3 Seasonal changes in hydrological characteristics along the urban transect for 2002. Precipitation (*Ppt*) was determined with a TE525 Tipping bucket rain gauge (Campbell Scientific); evapotranspiration (*ET*) was determined using a USWB Class-A Evaporation pan, and supplemental irrigation (*I*) to match ET was provided using tap water (i.e. no additional nutrients) at each site. Δ is the difference between estimated ET and water applied (*Ppt+I*). Water applied was slightly greater than ET at all sites for the growing season

Hydrological data (cm)				
Site	ET	Ppt	I	$\Delta(Ppt+I)-(ET)$
Rural	106.3	71.3	40.6	+5.6 (surplus)
Suburban	83.4	57.2	33.0	+6.7 (surplus)
Urban	90.8	61.1	34.3	+4.6 (surplus)

Measurements of NO₃ and NO₂ in rainwater indicated no significant difference in concentration between the rural farm and the suburban park. Although NO₃ and NO₂ values were significantly higher at the urban site (0.4 vs 0.1 μ m and 4.1 vs 1.5 nm, relative to the rural location), the concentration of nitrogen (i.e. μ m, nm) is minor (i.e. <0.1%) relative to the amount of N available within the soil at the start of the experiment.

Other micro-meteorological variables did differ slightly depending on location (most notably wind speed which was highest for the rural site). Overall however, no remaining meteorological factors differed consistently along the transect (Table 1).

What impact did the observed micro-meteorological changes have on plant growth? Seedling counts indicated a significant increase in total seedling number for the urban location relative to the rural site by April 10 (data not shown). For all sites, lambsquarters was the predominant species. Lambsquarters, sunflower, foxtail, ragweed, primrose and henbit comprised more than 90% of all seedlings present at each site. By the end of the growing season, biomass at all sites was dominated by sunflower and lambsquarters which, because of plant height, shaded out most competitors. Productivity (determined as above ground biomass) increased 60 and 115% for the suburban and urban sites, respectively (Table 4). The biomass accumulation values for the urban and suburban locations are considerably higher than those reported for other community-level studies in which [CO₂] alone was manipulated (e.g. DeLucia et al. 1999; Edwards et al. 2001; Morgan et al. 2001; Reich et al. 2001) and productivity for the urban site was extremely high (Cooper 1970). Both the suburban and urban sites were also differentiated by significant increases in plant height (lambsquarters) relative to the rural location (Table 4).

Among micro-meteorological factors, which showed the best correlation with productivity? Soil temperature for the first 30 days following frost in the spring demonstrated the strongest correlation ($r^2 > 0.98$), but seasonal daytime temperature and [CO₂] averages were also significant (Table 5). In contrast, no significant relationship was observed between productivity and other variables (night temperature, VPD and wind speed, Table 5).

Table 4 Productivity, determined as above ground biomass for plants at each location in the transect. Biomass is g m²; height was determined in centimeters for the tallest species at each location (lambquarters, *Chenopodium album* L.). Number of growing days is the number of days where the minimum temperature exceeded 0.0°C. Different letters within a column indicate significant differences between sites as determined by Fisher's protected least significant difference test ($P < 0.05$)

Productivity and height (±SE) by site		
Site	Biomass	Height
Rural	1,819±107 c	241±19.4 c
Suburban	2,932±193 b	286±15.4 b
Urban	3,896±52.5 a	338±25.4 a

Table 5 Regression analysis comparing productivity (dependent variable) along the transect to micro-meteorological seasonal averages (independent variables)

Regression analysis of micro-meteorological variables to productivity		
Variable	r ²	Regression
Soil temperature	0.98*	$y = -2,555.9 + 1032.6x$
Day temperature	0.88*	$y = -2,6366 + 1142.7x$
CO ₂	0.86*	$y = -6,517.5 + 22.5x$
Night temperature	0.61	$y = -4,039.1 + 488.5x$
VPD	0.46	$y = -2,336.4 + 6061.2x$
Wind speed	0.06	$y = 3,316.3 + -276.9x$

* P -value ≤ 0.05

Overall, urban-induced [CO₂], soil and daytime temperature gradients, consistent with most IPCC predictions, appeared to have a significant effect on productivity and plant height during the first year of secondary succession with minimal effects from other micro-meteorological components. Given the observed changes in height and productivity, and what is known concerning light requirement and seed size, we would hypothesize that a greater amount of dry mass returned to the soil with increased [CO₂] and temperature may significantly reduce light availability and the success of smaller seeded species, favoring the growth of perennial species and a subsequent increase in the rate of succession. However, the long-term implications of the CO₂/temperature gradient on secondary succession will require additional study.

An additional inference of the experimental data may be related to urban ecology per se. That is, [CO₂] and temperature differences between urban environments and surrounding rural areas may already be differentially affecting plant species. One assumption among plant biologists has been that the increase in CO₂ will be gradual, and that acclimation or down-regulation to such an increase will be widespread (DeLucia et al. 1985; Stitt 1991). If a distinct CO₂ and/or temperature gradient is already in place however, then a differential response to such an existing gradient will have significant ecological

implications for the success of plants which exploit anthropogenically disturbed (i.e. urban) areas.

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