Cities as harbingers of climate change: Common ragweed, urbanization, and public health

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Background: Although controlled laboratory experiments have been conducted to demonstrate the sensitivity of allergenic pollen production to future climatic change (ie, increased CO_2 and temperature), no in situ data are available.
Objective: The purpose of this investigation was to assess, under realistic conditions, the impact of climatic change on pollen production of common ragweed, a ubiquitous weed occurring in disturbed sites and the principal source of pollen associated with seasonal allergenic rhinitis.
Methods: We used an existing temperature/CO_2 gradient between urban and rural areas to examine the quantitative and qualitative aspects of ragweed growth and pollen production.
Results: For 2000 and 2001, average daily (24-hour) values of CO_2 concentration and air temperature within an urban environment were 30% to 31% and 1.8° to 2.0°C (3.4° to 3.6°F) higher than those at a rural site. This result is consistent with most global change scenarios. Ragweed grew faster, flowered earlier, and produced significantly greater above-ground biomass and ragweed pollen at urban locations than at rural locations.
Conclusions: Here we show that 2 aspects of future global environmental change, air temperature and atmospheric CO_2, are already significantly higher in urban relative to rural areas. In general, we show that regional urbanization-induced temperature/CO_2 increases similar to those associated with projected global climatic change might already have public health consequences; we suggest that urbanization, per se, might provide a low-cost alternative to current experimental methods evaluating plant responses to climate change. (J Allergy Clin Immunol 2003;111:290-5.)

Key words: *Global change, seasonal allergenic rhinitis, Amb a 1, common ragweed*

Abbreviation used
$[CO_2]$: Atmospheric CO_2 concentration

Climate change secondary to expanded fossil fuel use and deforestation has received considerable attention in recent decades.[1] Many investigations have focused on the impact of increasing atmospheric CO_2 concentrations ($[CO_2]$) on agronomically important crop and tree species.[2] Relatively little attention, however, has been paid to the medical implications[3] of increasing atmospheric $[CO_2]$, either directly—with respect to its effect on human physiology and pathophysiology—or indirectly—with respect to alteration of the physiology of plants associated with human disease.

The genus *Ambrosia*, which includes both *A artemisiifolia* (short or common ragweed) and *A trifida* (giant ragweed), has long been recognized as a significant cause of allergic rhinitis. A large random skin test survey demonstrated that 10% of the US population was ragweed-sensitive; the prevalence among atopic individuals was 27% in 2 large case series.[4-6] One authority reported, perhaps hyperbolically, that *A artemisiifolia* and *A trifida* cause more seasonal allergic rhinitis than all other plants combined.[7]

The ragweeds, like other plants with C_3-type photosynthesis, are currently carbon-limited. Accordingly, increases in $[CO_2]$ since the beginning of the industrial revolution should stimulate photosynthesis, vegetative growth, and pollen production. This was demonstrated by Ziska and Caulfield[8] in a highly controlled experiment involving ragweed reared in growth chambers: total biomass was directly correlated with increasing $[CO_2]$. Moreover, total pollen production per plant increased significantly over the range in $[CO_2]$ used. These findings were later replicated by a different group in a similar indoor investigation.[9]

Although provocative, these data had unclear implications for seasonal allergic rhinitis for 3 significant reasons. First, the range in $[CO_2]$ was broad and was based in part on predicted future $[CO_2]$; the impact of more modest $[CO_2]$ gradients is thus unknown. Second, the investigations altered $[CO_2]$ but held other variables constant; in typical climate change scenarios, both ambient air temperature and $[CO_2]$ increase concomitantly. Third, pollen production was demonstrated to increase as a function of $[CO_2]$, but the allergenicity of the resulting pollen was not measured. In the face of profound vegeta-

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tive changes, it seems inappropriate to assume no alteration in the pollen's protein metabolic machinery.

In the light of these limitations, we designed an outdoor experiment to more realistically address the impact of climate change on ragweed biology and associated allergic rhinitis. The present investigation considered ragweed grown along an urban transect with naturally co-occurring increases in temperature and [CO_2]. Phenologic events, vegetative growth, and pollen production were determined according to methods used previously. In addition, pollen was subjected to immunochemical analysis to quantify Amb a 1 content.

METHODS

Ragweed establishment

Beginning in April 2000, a transect involving rural (Buckeystown), semirural (Carrie Murray Nature Center), suburban (Towson University), and urban (Baltimore Science Center) locations was established within Maryland. Seed (*A artemisiifolia*) was obtained from Valley Seed Company (Fresno, Calif) from a common seed lot of ragweed. All seeds were mixed and distributed randomly into a common soil type at monitoring sites along the transect. The common soil is classified as a Cordurus silt-loam with pH 5.5 and high availability of potash, phosphate, and nitrate (*Cordurus hatboro*).

Plants were thinned to 1 plant per 27,000 cm^3 of soil within an enclosure (average, 1 plant per 730 cm^2 of surface area [approximately 14 plants per square meter]) by maturity. In 2000, top growth was harvested at anthesis and maturity; in 2001, top growth was harvested at 2-week intervals until anthesis and again at maturity. At final harvest, (90% senescence of above-ground structures), entire plants were collected en bloc to a soil depth of 30 cm.

Sites were watered with tap water that was brought to each site to equalize rainfall differences. Nitrate (NO_3) and nitrite (NO_2) rainwater content was measured in 2001 by means of ultraviolet spectroscopy after HPLC to achieve separation (NO_3) and colorimetry with sulfanilamide (NO_2), respectively—our purpose being to quantify nitrogen deposition along the transect.

Weather stations

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), a temperature and humidity probe (CS500), a 6-plate radiation shield (41301 RM), a rain gauge (TE 525), and an infrared CO_2 analyzer (S151, Quibit Systems, Kingston, Ontario, Canada). A quantum sensor (LI190SB; Li-Cor Corporation, Lincoln, Neb) was also deployed.

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-minute intervals and downloaded weekly through use of a storage module (SM192; Campbell)) and keypad (CR10KD; Campbell). All Campbell equipment arrived from the factory in a precalibrated state. CO_2 analyzers were calibrated monthly for each site.

Pollen sampling and assessment

Rotorod Samplers (model 20; Sampling Technologies, St Louis Park, Minn) were installed 1.5 m above grade in circular arrays (3 samplers per array) 1 m from the edge of each test plot.[10] Atmospheric samples were obtained on an intermittent (modified 10% duty cycle) but synchronous basis with retracting heads and duty cycle timers (model 30).

Collector rods were prepared and processed under standardized conditions by a single analyst.[11] Resulting pollen data were converted to volumetric equivalents (pollen grains per cubic meter of air) and aggregated for each sampling period by site. All samplers were calibrated at the beginning and end of each growing season to ensure proper performance.[12]

Immunochemistry

To determine qualitative changes in pollen, harvested pollen grains or crushed florets were suspended in a small volume (~20 μL) of 95% ethanol. Nine volumes of 1% Tween 20 in 0.03 mol/L $NaHCO_3$ containing 0.5% NaCl were added. The resulting suspensions (200 μL) were sonified for 30 seconds at 4°C through use of a Sonic Dismembrator 550 (Fisher Scientific, Hampton, NH) equipped with a microtip (3.18 mm diameter) set to 10% power output; the sonified suspensions were held at 4°C overnight. Solid particles were removed by centrifugation (16,000*g* for 5 minutes). The crude soluble pollen protein preparations were stored at –20°C. (Glycerol was added to prevent the extracts from freezing.) Protein concentrations in each of the final extracts ranged from 0.21 to 0.31 mg/mL. Protein content of the extracts was quantified as described by Bradford[13] and modified by Spector.[14] Ragweed pollen protein Amb a 1 (ie, antigen E) was quantified through use of a modified kinetic-based ELISA method.[15,16] Pollen protein samples were diluted initially to 2.5×10^{-4} mg/mL, and a linear dilution series of each of these solutions was distributed into a 96-well ELISA plate (Nunc-Immuno MaxiSorp Plates, Nalge Nunc International, Roskilde, Denmark). Sheep anti–Amb a 1 was a generous gift of Dr J. E. Slater of the CBER/FDA laboratory (Rockville, Md); horseradish peroxidase–labeled rabbit-antisheep IgG was obtained from Kirkegard and Perry (Gaithersburg, Md). Plates were developed through use of 1 mmol/L H_2O_2 and 2 mmol/L 2,2′-azino-*bis* (3-ethylbenzthiazoline-6-sulfonic acid) in 0.2 mol/L sodium phosphate, –0.10 mol/L citric acid buffer, pH 5.0.[15,17] The rate of color development was measured at 415 nm. We defined the amount of antigen present using an arbitrary ELISA unit: $U = \Delta A@_{415nm}$/min.

RESULTS

Urbanization-induced environmental change

Both [CO_2] and ambient air temperature were related to the level of urbanization. Urbanization increased the average daily (24-hour) [CO_2] by 30% and 31% in 2000 and 2001, respectively, in comparison with the farm site, the absolute CO_2 values being consistent between years for each site (Table I). Dividing cumulative degree differences by the number of growing degree days for ragweed gave average daily temperature increases of 0.7°/0.6°, 1.0°/1.1°, and 1.9°C for the semirural, suburban, and urban sites for 2000/2001, respectively, relative to the rural site. Although 2001 was a warmer year than 2000, the temperature gradient along the transect relative to the rural site was consistent between years. In general, the increases in temperature and [CO_2] observed along the transect are consistent with the short-term (~50 year) projections for CO_2 and temperature made by the Intergovernmental Panel on Climate Change.[1] Absolute CO_2 values observed for Baltimore are also consistent with recent 2-week estimates along a suburban-urban transect reported for the city of Phoenix, Ariz.[18]

Other environmental variables

Remaining meteorologic variables did not differ consis-

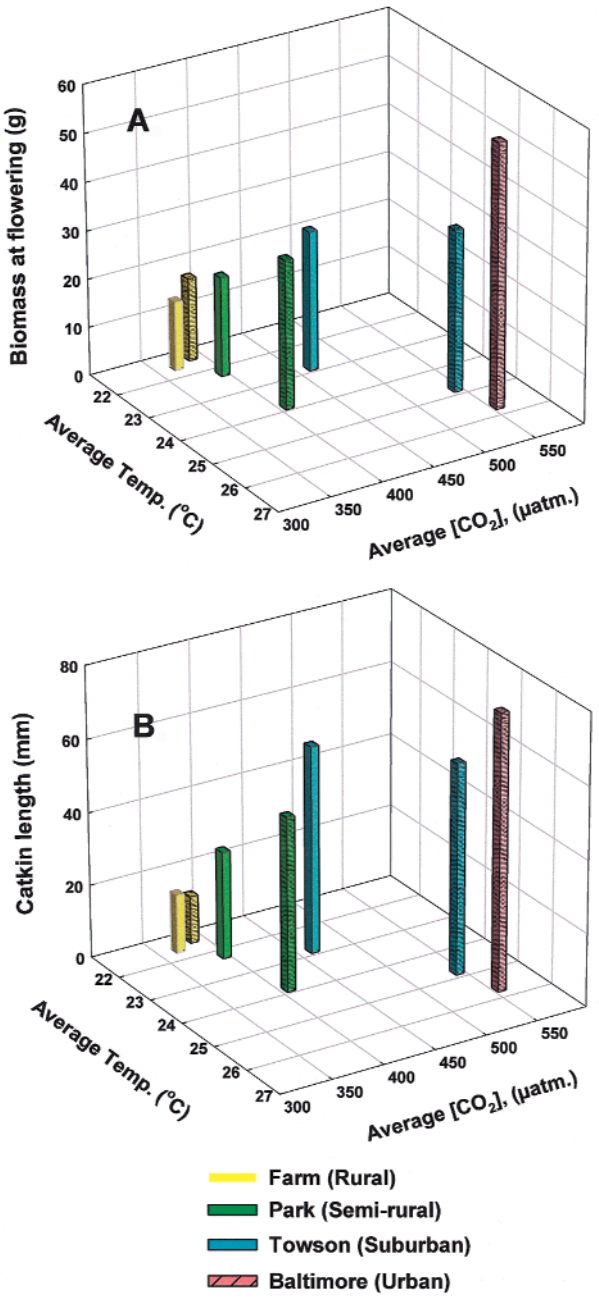

FIG 1. Biomass **(A)** and average catkin length **(B)** during anthesis for ragweed (per plant) as a function of [CO_2] and air temperature during the pollen release period. *Open bars* and *hatched bars* are for 2000 and 2001, respectively. Catkin length is the average for the first 3 weeks after anthesis.

tently along the transect for each year (Table II). As expected, ozone values were high (relative to accepted standards of the US Environmental Protection Agency[19]), *though peak hourly ozone exposure did not vary along the transect (in part because of high ozone levels from the Ohio valley).

*A complete description of ozone values for any given day for monitoring sites in Maryland can be found at www.epa.gov/air/oaqps/cleanair.html.

To determine whether such levels could alter ragweed growth, a separate sensitivity analysis using the same seed lot was conducted. This analysis indicated no effect of urban ozone levels on ragweed biomass or reproductive growth through anthesis.[20] Measurements of NO_3 and NO_2 in rainwater for 2001 indicated no differences in concentration for the rural farm, the semirural park, or the suburban site (Table II). Whereas NO_3 and NO_2 values were significantly higher at the urban site (0.442 µmoles and 3.56 nmoles), the concentration of nitrogen (ie, µmole, nmole) was probably insufficient to alter ragweed growth.

Growth response of ragweed

Above-ground biomass at floral initiation was related to the level of urbanization (Fig 1, *A*). In 2001, ragweed seed emerged 3 or 4 days earlier at the urban site than at the rural site, but senescence also occurred earlier as a result of urbanization, lowering the relative enhancement of growth along the transect when biomass at maturity is compared with biomass at anthesis. By maturity, aboveground biomass had increased by 8% to 10% at the semirural site and 61% to 66% at the suburban site in 2000 and 2001 and by 189% at the urban site in 2001 in comparison with the rural site.

Reproductive response of ragweed

Urbanization-induced increases in both [CO_2] and air temperature resulted in significant increases in catkin length by floral initiation (Fig 1, *B*). Dates of pollen collection, peak amounts, and total pollen collected indicated a greater amount of pollen production in 2001 than in 2000, earlier and greater amounts of pollen occurring as a function of urbanization (Table III and Fig 2). The large jump observed in pollen production from the rural site to the suburban site is associated with a significant increase in average CO_2 concentration, which is consistent with the CO_2 sensitivity of pollen production observed in previous laboratory studies.[8]

Allergen content of ragweed

Qualitatively, differences in antigen levels obtained from the suburban, semirural, and urban sites were not significant (9.0-11.1 U per microgram of protein). However, a significantly higher quantity of antigenic protein was extracted from rural farm site pollen (16.4 ± 0.7 U per microgram of protein; $P < .01$).

DISCUSSION

There has been considerable speculation about the medical implications of climate change.[3] Previous laboratory-based investigations suggesting greater potential for seasonal allergic rhinitis resulting from CO_2 included stimulations of ragweed pollen production.[8,9] However, the applicability of these results to in situ conditions remained speculative. To reduce speculation, the current experiment sought to use urban environments as a surrogate for future climatic change to provide a realistic, real-time means of evaluating ragweed pollen production.

TABLE I. Locations and descriptions of data collection sites along the rural/urban transect

Site	Description	[CO_2]	CDD (°C)	Difference	+Avg (°C)
2000					
Organic farm	Rural site—control	386 ± 19.0[b]	3428.4	0	
Nature center	County park—semirural	398 ± 5.5[b]	3543.3	114.9	+0.7[b]
Towson University	Baltimore suburb	461 ± 35.1[a]	3599.5	171.1	+1.0[a]
2001					
Organic farm	Rural site—control	389 ± 18.1[b]	3514.2	0	
Nature center	County park—semirural	399 ± 21.9[b]	3612.3	98.1	+0.6[c]
Towson University	Baltimore suburb	501 ± 55.9[a]	3692.2	178.0	+1.1[b]
Science center	Downtown Baltimore—urban	511 ± 46.6[a]	3854.5	340.3	+1.9[a]

Data are average concentrations of atmospheric CO_2 (μatm ± SE), cumulative degree days (in degrees Celsius), cumulative degree day differences, and average increases in daily temperature relative to the organic farm site. All data were determined as daily (24-hour) averages along an urbanization gradient from day of year (DOY) 93 through DOY 270 for 2000 and 2001. The period DOY 93 through DOY 270 corresponds approximately to the growing season for common ragweed at this latitude. Note that permission from city authorities to grow ragweed was not given for downtown Baltimore (the Science Center) in 2000. Data were analyzed for each year through use of a 1-way ANOVA with site (ie, CO_2/temperature gradient) as the classification variable. Different superscript letters for CO_2 and average increase in daily temperature indicate significant differences between sites as determined by Fisher's protected least significant difference test ($P < .05$).
CDD, Cumulative degree day; *+Avg,* average increase in daily temperature (in degrees Celsius).

TABLE II. Measured climatic and air quality characteristics along the urban transect on an average (24-hour) basis during the period DOY 93 through DOY 270 for 2000 and 2001

Site	RH	PAR (μmol m^2/s)	WS (m/s)	O_3 (ppb)	NO_2 (nmol/L)	NO_3 (μmol/L)
2000						
Rural	79.1	332	1.8[a]	102	—	—
Semirural	77.0	307	0.4[b]	—	—	—
Suburban	77.5	311	0.7[b]	105	—	—
2001						
Rural	61.9	431	2.1[a]	111	1.08[b]	0.22[b]
Semirural	63.5	381	0.7[b]	—	0.91[b]	0.19[b]
Suburban	63.6	425	0.4[b]	113	0.33[b]	0.20[b]
Urban	62.7	434	2.9[a]	106	3.56[a]	0.44[a]

O_3 levels are peak hourly averages from May through September determined at US Environmental Protection Agency (EPA) monitoring sites in the western part of Maryland (Frederick County), in Baltimore County, and in Baltimore City, which approximately correspond to the rural, suburban, and urban sites for the transect; note that sulfur dioxide (SO_2) values did not exceed EPA standards for any part of the state (for a complete description of sites and air quality values, see www.epa.gov/air/oaqps/cleanair.html). Nitrite (NO_2) and nitrate (NO_3) were determined in dissolved rainwater for 2001, as described in the Methods section. A separate study of ozone sensitivity for this seed lot indicated no effect of average urban ozone levels on ragweed biomass or reproductive growth through anthesis.[20] Different superscript letters within a given column for a given year indicate significant differences as determined by Fisher's protected least significant difference test ($P < .05$). See the Methods section for additional details.
RH, Relative humidity; *PAR,* photosynthetically active radiation (ie, radiation between 400 and 700 nm); *WS,* wind speed.

It is clear that the 2 principal environmental parameters expected to increase with global climate, ambient air temperature and [CO_2], also increase in response to urbanization. As a result, the experimental approach described here represents a novel alternative to other field-based methods, such as open-top chambers[21] and free-air CO_2 enrichment,[22] which have been used to simulate future climates. The use of the urbanization transect in the current experiment offers an alternative, "cost-friendly" approach to providing concurrent temperature and [CO_2] increases that are consistent with most climate change scenarios. As such, urbanization per se might provide an effective and relevant means of assessing the future impact of climate change on biological systems.

More importantly, our data indicate that urban environments might already be subject to the kinds of higher temperatures and CO_2 concentrations that are projected for the next 50 to 75 years for the planet as a whole.[1] Consequently, existing differences in CO_2 levels and air temperature between urban and rural environments might already be affecting plant growth and fecundity. A differential physiologic response to such an existing urbanization gradient will have significant ecologic implications, particularly for the success of weedy plants that exploit anthropogenically disturbed areas. In the current experiment, for example, it is clear that the urbanization-induced environmental differences are sufficient to alter the growth and reproductive cycle of common ragweed over a 2-year period in situ.

It is this latter finding that could be of particular significance with respect to public health. The differential response of ragweed along the urban transect demonstrated several important medical implications of climate change.

First, earlier phenologic events occurred with urbanization-induced environmental change—eg, both seed emergence and floral initiation occurred earlier at the

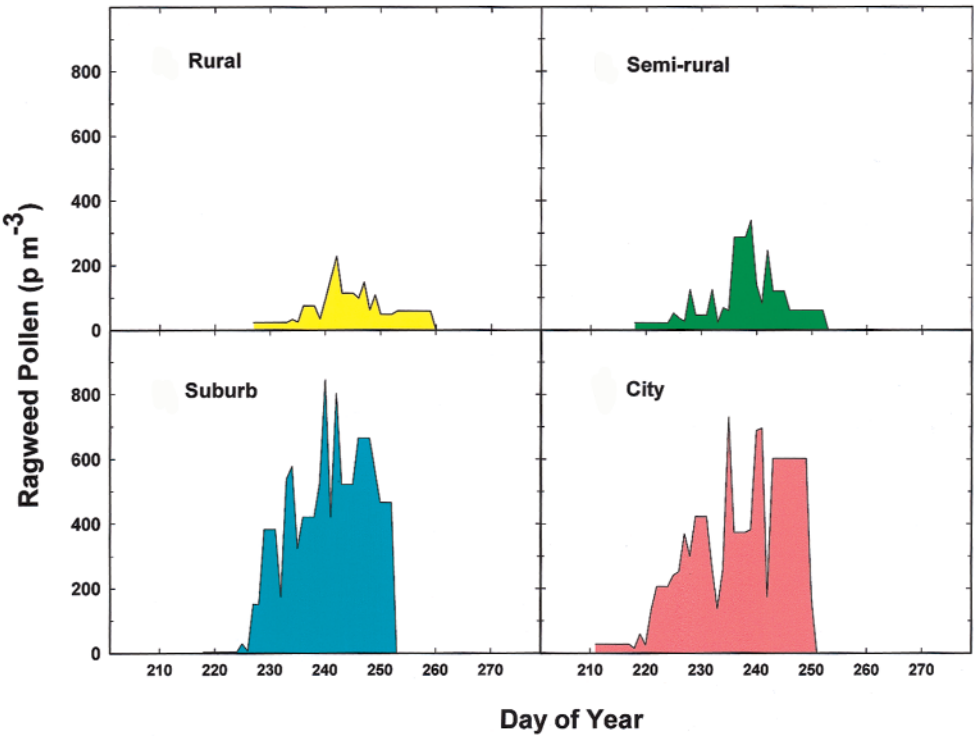

FIG 2. Time course of ragweed pollen production for 4 sites along an urban transect for 2001 as a function of day of year. Values are numbers of pollen grains per cubic meter of air.

TABLE III. Data collection of pollen from common ragweed along the urban transect

Site	Dates of collection	Peak amount	Date on which peak was collected	Pollen sum	Pollen average
2000					
Rural	Aug 14–Sep 26	211[c]	Sep 4	1751[b]	39.8[b]
Semirural	Aug 8–Sep 18	481[b]	Aug 31	1881[b]	44.8[b]
Suburban	Aug 8–Sep 26	724[a]	Sep 8	6537[a]	130.7[a]
2001					
Rural	Aug 15–Sep 17	228[b]	Aug 30	2294[b]	69.5[b]
Semirural	Aug 6–Sep 10	338[b]	Aug 27	3262[b]	93.2[b]
Suburban	Aug 6–Sep 10	845[a]	Aug 27	13204[a]	377.3[a]
Urban	Jul 30–Sep 7	729[a]	Aug 23	12138[a]	311.2[a]

Higher-than-expected peak amounts for the nature center site in 2000 were obtained from extraneous ragweed growing near the Rotorod Samplers. For each collection site, *Pollen sum* and *Pollen average* are the total amount of pollen collected and the average pollen amount, respectively. The amount of pollen collected is given in grains per cubic meter. Pollen collection began with establishment of floral catkins. Different superscript letters within a given column for a given year indicate significant differences as determined by Fisher's protected least significant difference test ($P < .05$).

urban site than at the rural control site. This phenomenon is consistent with recent data on earlier flowering times in response to warming temperatures over the last decade in the United Kingdom.[23] Although floral development is generally considered to be controlled by photoperiod in ragweed, our data demonstrated small but measurable phenologic differences as a function of temperature and [CO_2]. Because floral initiation precedes anthesis, pollen shed occurred earlier at the more urbanized sites (Fig 2). These observations suggest that climate change can alter the general characteristics of the ragweed pollen season.

Second, above-ground and catkin biomass increased with urbanization-induced environmental change. As a consequence, greater atmospheric pollen counts were observed along the transect, thus establishing for the first time a relationship between climate change and an accepted surrogate for human exposure to pollen. Although human subjects were not a feature of this investigation, one might anticipate differences in both the prevalence of seasonal allergic rhinitis and symptom scores along the transect.[24] Additional experiments will be required to examine these epidemiologic phenomena.

Third, ragweed pollen at the rural site contained more allergen than pollen obtained from the urban site, though there was no clear demarcation in response to urbanization. The environmental basis for qualitative differences remains unclear. That is, soil nitrogen content cannot explain differences between suburban and rural locations, herbicides

were not used at (or adjacent to) any of the sites, and other climatic factors did not vary consistently. The underlying physiologic basis for qualitative differences in pollen is also unclear, inasmuch as the functions of most antigenic pollen proteins, including Amb a 1, are unknown. The observed differences might be consistent with prior experiments that demonstrated an inverse relationship between tissue nitrogen content and [CO_2].[25] These findings are also consistent with data from Illinois indicating that antigen E levels vary in response to growth location.[26]

The finding concerning allergen content demonstrates that the medical implications of climate change are not straightforward. Although atmospheric ragweed pollen counts increased along the transect, allergen content relative to total protein was highest for the rural control. On a net basis, more atmospheric allergen was likely present in the urbanized areas; however, the human impact would be exceedingly difficult to predict. As noted previously, further clinical investigations are required to address these issues.

Despite the need for additional clinical information, this research demonstrates that climate change—perhaps on a much finer scale than previously appreciated—can alter plant physiology and reproductive behaviors in ways that are already likely to be affecting human health. Accordingly, the epidemiology of plant-induced allergic rhinitis, in compact urban areas[27] as well as on a global basis,[28] can be expected to change as a result of environmental change. Although the current research describes a single plant species, urbanization, empirically speaking, would also be expected to influence seasonal pollen production of other allergenic plants, including tree and grass species. Overall, the methods used and the results obtained should stimulate both botanists and health care providers to delve further into anthropogenic climatic and/or meteorologic factors that alter the quantitative and qualitative aspects of allergenic pollen.

Conclusions

Field-based data over a 2-year period indicated that 2 specific factors related to urbanization and future climatic change—namely, increased [CO_2] and air temperature—significantly influence the phenology, pollen production, allergenicity, and subsequent atmospheric pollen concentration of common ragweed. Accordingly, urbanization appears to act as a surrogate for global change. The elementary example given here demonstrates strong probable links between rising CO_2 levels, global change, and public health.

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