

Crop physiological response across the Chicago metropolitan region: Developing recommendations for urban and peri-urban farmers in the North Central US

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From the Field for Themed Content: Urban Agriculture

Abstract

Despite the surge of interest in urban agriculture, there have been few studies that address the biophysical challenges and opportunities of food production in urban environments. This study aims to determine the relative influence of atmospheric pollutants and microclimatic factors on the physiological response and productivity of vegetable crops across an urban-to-rural latitudinal transect in the greater Chicago metropolitan region. Data collected at each of six sites include continuous measures of atmospheric pollutants and microclimatic factors, and biweekly measures of physiological response and yield of various vegetable crops and cultivars. Preliminary data collected in early 2013 suggest that there is substantial variability in environmental factors and crop yield across this urban-to-rural transect. Results of this study will provide a scientific basis for crop adaptation to the urban environment and establish practical crop and cultivar recommendations for urban and peri-urban farmers in the North Central US.

Key words: urban agriculture, urban gardening, vegetable crops, plant ecophysiology

Introduction

Urban agriculture can be defined as all forms of agricultural production (food and non-food products) occurring within or around cities. Urban agriculture is unique from rural agriculture in that farmers have the opportunity to use or reuse urban resources (e.g., labor, materials and waste products) and in return provide agricultural products and services to urban areas¹. The most common form of urban agriculture in the US is fruit and vegetable production, which occurs in home and community gardens, vacant lots, controlled environments (e.g., greenhouses) and on rooftops. While home gardening is a historically popular hobby in the US, urban agriculture is now emerging as a commercial sector of local food economies. As the concentration of people living within urban areas around the world increases², urban agriculture may contribute to increased food security, food safety, nutrition and food equity within cities^{3,4}. Urban food production is seen as a sustainable reuse of vacant land and greenspace in urban areas because of close proximity to consumers, efficient utilization of land

resources, and community and social benefits^{5,6}. Urban agricultural activities are already underway in major metropolitan areas of the US, but there is limited science-based information available to urban farmers regarding the cultivation of plants in urban environments⁷.

The vast majority of agricultural scientific knowledge has been obtained through field experimentation in rural growing environments, but there is increasing evidence to suggest that the urban atmospheric growing environment is substantially different from the rural environment⁷. Some aspects of the urban environment, including elevated ambient CO₂ and temperatures, can positively influence plants via carbon fertilization effects and an effectively longer growing season^{8,9}. However, plants may be negatively affected by elevated concentrations of atmospheric pollutants (e.g., O₃, volatile organic carbons and NO_x) and extreme heat in urban areas^{10,11}. Atmospheric concentrations of CO₂ are elevated in dense urban areas due to increased human activity and fossil fuel combustion^{12,13}. In the absence of heat and moisture stress, elevated CO₂ has been shown to increase plant productivity and fruit yield¹⁴. Elevated CO₂ can also reduce plant

water use due to reductions in stomatal conductance, but this effect is accompanied by reduced plant transpiration that can lead to increased canopy temperature and plant stress¹⁵.

Ozone is also elevated in and around urban areas due to a variety of anthropogenic activities, and can have phytotoxic effects on plants^{10,16,17}. Current tropospheric ozone levels can be damaging to crop yields and future projections suggest concentrations will increase¹⁸. Plants are vulnerable to ozone damage due to the sensitivity of the photosynthetic pathway to oxidative stress¹⁸, and elevated tropospheric ozone has been shown to reduce photosynthesis and root:shoot ratio in plants¹⁷. However, large variation in ozone susceptibility has been shown among species¹⁹. Ozone is also a potent greenhouse gas that may contribute to increased thermal radiation and temperatures in cities²⁰. Ozone concentrations and fluxes in metropolitan regions are variable due to the reactive nature of ozone, but the levels can be two to four times greater in urban areas relative to adjacent rural areas during high flux periods^{20,21}. However, because ozone readily oxidizes nitrous oxides and other reduced materials in the urban atmospheric environment, ozone concentrations are often greater in downwind rural areas adjacent to cities²².

In addition to atmospheric pollutants, crops growing in urban environments are influenced by elevated temperatures²³, reduced wind speed²⁴, shading and increased moisture stress²⁵. The elevation of temperatures in urban areas can be beneficial if it extends the growing season for farmers⁹ because it may provide opportunities to grow crops and cultivars not typical in the region, or to double crop and increase profitability per unit area. Unfortunately, elevated average urban temperatures are typically accompanied by extreme daytime temperatures and elevated night-time temperatures, which have been shown to limit plant growth^{26,27}. Reduced wind speeds in urban areas are the result of the built environment, which can act as an artificial windbreak, reducing plant mechanical damage and increasing yields^{24,28}. However, reduced wind speed can contribute to increased temperature and vapor pressure deficit (VPD). Elevated VPD in cities will increase plant transpiration and moisture stress, placing a greater demand on supplemental irrigation water^{7,25}.

Effects of the urban atmospheric environment on plants are complex and many factors are interrelated. To better understand the complex relationship between plants and the urban environment, we established a 3-year *in situ* experiment in 2013 to accomplish three specific objectives: (1) characterize the atmospheric environment along an urban-to-rural latitudinal transect through the Chicago, IL metropolitan region, with regular measurements of ambient CO₂, tropospheric ozone, temperature, light intensity, VPD and wind speed; (2) quantify crop and cultivar plant physiological response to altered environmental conditions along this urban-to-rural latitudinal transect; and (3) determine the relative influence of each

environmental factor on crop and cultivar physiological response. Results of this study will establish a scientific understanding of crop physiological response and adaptation to the urban environment, and also provide practical crop and cultivar recommendations for the growing population of urban and peri-urban farmers in the North Central US.

Materials and Methods

Six individual research sites were established along an urban-to-rural latitudinal transect (approximately 41°51'N) in the Chicago, IL metropolitan region in March 2013 (this marks the first year of a 3-year study). The most rural site is located in Maple Park, IL (41°52'50"N; 88°33'41"W) and the most urban site (relative to downtown Chicago) is located 72 km east in the East Garfield Park neighborhood of Chicago, IL (41°53'15"N; 87°43'02"W) (Supplementary Figure 1). At each site, 40 fabric pots (378.5 liters; 96.5 cm wide × 50.8 cm deep; Smart Pots, High Caliper Growing—Root Control, Inc., Oklahoma City, OK) were filled with a uniform nutrient sufficient soil–compost mix (12.8% OMC; pH = 8.1; 62% sand; 22% silt; 16% clay by texture) and equipped with drip irrigation soaker tubes (Dripworks, Inc., Willits, CA) set on a timer to deliver 9.5 liters of water per pot per day to satisfy crop water demand throughout the growing season (Supplementary Figure 2). Five soil water sensors (Watermark 200SS; Irrrometer Company, Inc., Riverside, CA) were buried to a depth of 10 cm in random pots at each site to ensure soil moisture is maintained near field capacity and does not become limiting to crops.

The experiment is arranged in a randomized complete block design with eight replicates nested within four blocks, and ten possible crops or cultivars planted at any one time within each replication across six sites. An imagined line divided the surface of each pot in half, creating two experimental units per pot for a total of 80 experimental units per site (Supplementary Figures 3 and 4). The number of individual crops planted in each experimental unit varied by crop, depending on size, ranging from one (e.g., tomato and zucchini) to eight (i.e., onion) plants per experimental unit.

A total of 12 unique crop species or cultivars were transplanted into experimental units at each site between April 11, 2013 and July 24, 2013. Crops and cultivars included: three tomato cultivars (*Solanum lycopersicum* cvs. Virginia Sweets, Granadero and Sungold), two pepper cultivars (*Capsicum annuum* cvs. Bounty and Antohi Romanian), two cultivars of snap bean (*Phaseolus vulgaris* L. cvs. R123 and S156), onion (*Allium cepa* cv. Candy), zucchini (*Cucurbita pepo* cv. Safari), kale (*Brassica oleracea* cv. Winterbor), beet (*Beta vulgaris* cv. Merlin) and Brussels sprouts (*Brassica oleracea* var. gemmifera cv. Diablo). Beets were double-cropped behind

kale and Brussels sprouts were double-cropped behind sweet onion, planted on July 24, 2013 and August 1, 2013, respectively. Crop species and cultivars were selected because of previously demonstrated susceptibility to atmospheric pollutants²⁹ and extreme weather conditions³⁰, differences in growth characteristics (e.g., cool season versus warm season crops³¹), and popularity among urban farmers (unpublished data). For example, one cultivar of snap bean has demonstrated tolerance to ground-level ozone (R123), whereas the other is susceptible (S156)²⁹.

Plant physiological measures vary by crop, but include measures of leaf chlorophyll (atLEAF light transmittance meter; FTGreen, LLC, Wilmington, DE), leaf area index (CI-202; CID Bio-Science, Inc., Camas, WA), plant height, stem diameter, marketable yield and final plant biomass. Microclimatic factors and atmospheric pollutants are being monitored at each site in an effort to explain variability in plant physiology across sites (Supplementary Figure 5). Data collected include ambient concentrations of CO₂ (SPA-5 CO₂ IRGA; PP Systems, Amesbury, MA) and ozone (F12; Ozone Solutions, Inc., Hull, IA), temperature and relative humidity (CS215; Campbell Scientific, Inc., Logan, UT), wind speed (cup anemometer 18860-90; R.M. Young Comp., Traverse City, MI) and direction (wind vane 7911; Davis Instruments, Hayward, CA), and photon flux density (SP-110 pyranometer; Apogee Instruments, Inc., Logan, UT). All sensors are connected to a factor corrected data logger (CR10X; Campbell Scientific, Inc., Logan, UT) and data points are logged every 20 min. Each site is visited by researchers at least three times per month to collect plant physiological data, harvest and download environmental data from loggers. Because all experimental sites are 2–3 h from campus, we are collaborating with community volunteers and University of Illinois Master Gardeners to collect harvest data for indeterminate crops (i.e., tomato, zucchini, beans and peppers) at all sites. Volunteers were trained on harvest procedures at the beginning of the season and an experimental protocol, data sheets, scales, bags and harvest knives are stored at each site.

Preliminary yield data presented here were analyzed with a mixed models analysis of variance with site as the fixed effect, replication as the random effect, and kale yield as the response variable (Proc GLIMMIX; SAS 9.3, SAS Institute Inc., Cary, NC, USA). Daytime and night-time means of environmental data were calculated for each site (where data were available) to serve as a preliminary method of comparison, but these data have not yet been statistically analyzed. Future analyses will seek to explain variation in plant physiology and yield among sites with environmental data using multivariate methods. Partial least squares regression is one potentially suitable multivariate method that has been used previously to relate environmental data to variability in plant demography and growth among locations³².

Results and Discussion

Environmental data

Mean daytime (07.00–19.00 h) and night-time (19.00–07.00 h) environmental data from the six experimental sites for the period of June 13 to July 24 2013 are summarized in Fig. 1. Data missing from individual sites for individual metrics were either the result of a missing instrument (e.g., only three ozone sensors were deployed in this study) or temporary sensor malfunction.

Average daytime temperature differed <1°C between rural (Kuiper's) and urban (Honore St. and Garfield) sites (ranging from 25.8 to 26.5°C), but night-time temperatures were more than 2°C warmer at the urban sites relative to the rural site, ranging from 19.5 to 21.7°C (Fig. 1). The substantial night-time temperature cline from urban to rural sites is consistent with the results of George et al.³³. In the absence of extreme heat and plant stress, elevated night-time temperatures may accelerate plant physiological development (e.g., accumulation of thermal heat units) and lead to greater productivity in urban areas for certain crops²³. However, elevated night-time temperatures have also been shown to inhibit photosynthesis and crop yield²⁷. Daytime solar radiation intensity ranged from 471 Wm⁻² at St. Charles (peri-urban) to 508 Wm⁻² at Kuiper's (rural) (Fig. 1). Light intensity did not follow a predictable spatial cline and instead seemed to be most influenced by proximity to surrounding tree canopies. The St. Charles, Cantigny and Cantata sites are surrounded by trees and reduced mean daytime solar radiation may be the result of partial light attenuation of the canopy during brief dawn and dusk hours. The 4.2% reduction in solar radiation at Garfield (urban) relative to Kuiper's (rural) in the absence of adjacent tree canopies may be the result of light attenuation by urban air pollutants (e.g., smog)³⁴.

VPD, the difference between actual and saturated atmospheric moisture, was on average 11.5% greater at urban sites (Honore St., Garfield and Cantata) than at peri-urban sites (Cantigny and St. Charles) during daytime hours (Fig. 1). VPD increases with temperature, which helps to explain elevated daytime and night-time VPD in urban relative to peri-urban sites of this study. Elevated VPD can lead to increased plant transpiration, water stress in the absence of adequate soil moisture, and disease and pest pressure²⁵. Wind speed generally decreased from rural to urban sites, with the exception of the Garfield site (Fig. 1). Elevated wind speed at the urban Garfield site may be related to a lower density of trees and built structures in the area, but this anomalous response requires further investigation. Bang et al.²⁴ reported increased plant productivity due to reduced wind speed in the urban environment, but this response may be specific to water-limited environments where wind can increase transpiration and plant moisture stress. Given adequate soil moisture (as is provided in this study), increased wind speed may lead to changes in plant

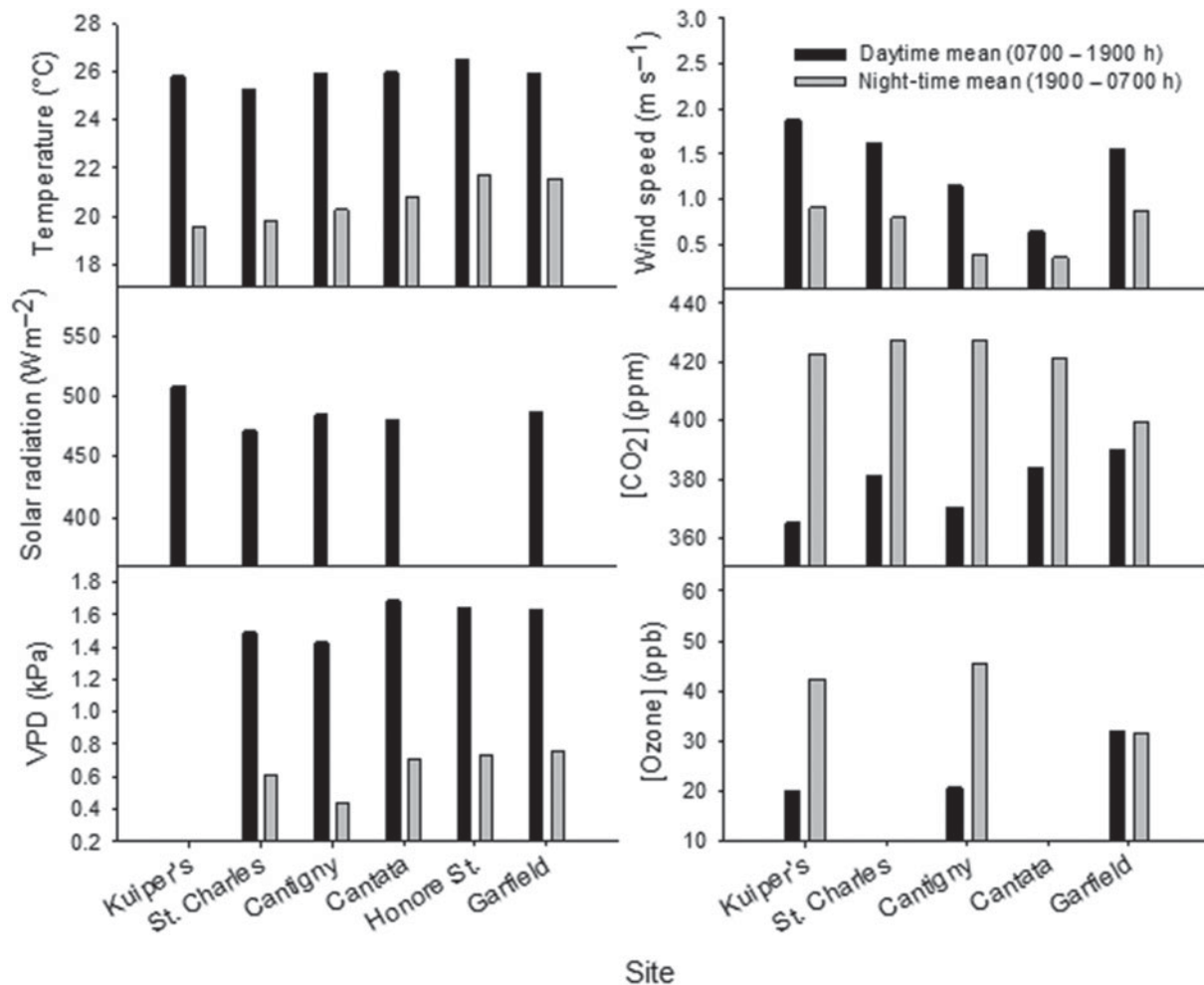


Figure 1. Daytime (07.00–19.00 h) and night-time (19.00–07.00 h) means of environmental data measured between June 13, 2013 and July 24, 2013 at six sites located along a rural (Kuiper's) to urban (Cantata, Honore St., and Garfield) latitudinal transect (sites are arranged from left to right on the *x*-axis in order of decreasing distance from Chicago city center). Environmental measures include temperature (°C), solar radiation (W m^{-2}), VPD (kPa), wind speed (m s^{-1}), CO_2 concentration (ppm), and ozone concentration (ppb). Missing data are due to the lack of a sensor at the site (e.g., ozone sensors only installed at three sites) or sensor malfunction (e.g., Kuiper's VPD).

architecture (e.g., shorter plants with thicker stems) without adverse effects on yield³⁵.

Daytime CO_2 concentrations generally were lower in rural compared to urban sites, ranging from 365 ppm at Kuiper's (rural) to 390 ppm at Garfield (urban). In contrast, night-time CO_2 concentrations were greatest in rural and peri-urban areas, ranging from 427 ppm at St. Charles and Cantigny (peri-urban) to 399 ppm at Garfield (urban). Elevated night-time CO_2 concentrations at rural and peri-urban sites may be related to the density of vegetation surrounding each site, because plants will respire and become a source of atmospheric CO_2 at night³⁶. The peri-urban and rural sites in this study are surrounded by either urban forest (Cantigny) or row crop fields (St. Charles and Kuiper's), whereas the most urban site (Garfield) is surrounded by a higher density of concrete and built structures. The 25 ppm difference in daytime CO_2 concentration observed between the most urban

and rural sites of this study is modest compared to the 66 and 122 ppm urban-to-rural contrasts reported by George et al.³³ and Ziska et al.²³, respectively, in the Baltimore, MD metro region. Daytime ozone concentration was greatest at the most urban site (32 ppb at Garfield) compared to the peri-urban (21 ppb at Cantigny) and rural (20 ppb at Kuiper's) sites. In contrast, night-time ozone concentrations were greatest at the peri-urban and rural sites and lowest at the urban site (Fig. 1). Elevated ozone concentrations in urban relative to rural environments have been shown to cause significant damage to plant growth³⁷.

Kale yield

Kale yield among sites varied depending on the harvest interval, but total yield was greatest at Garfield (the most urban site) (Fig. 2). Total yield ranged from 2723 g plot^{-1}

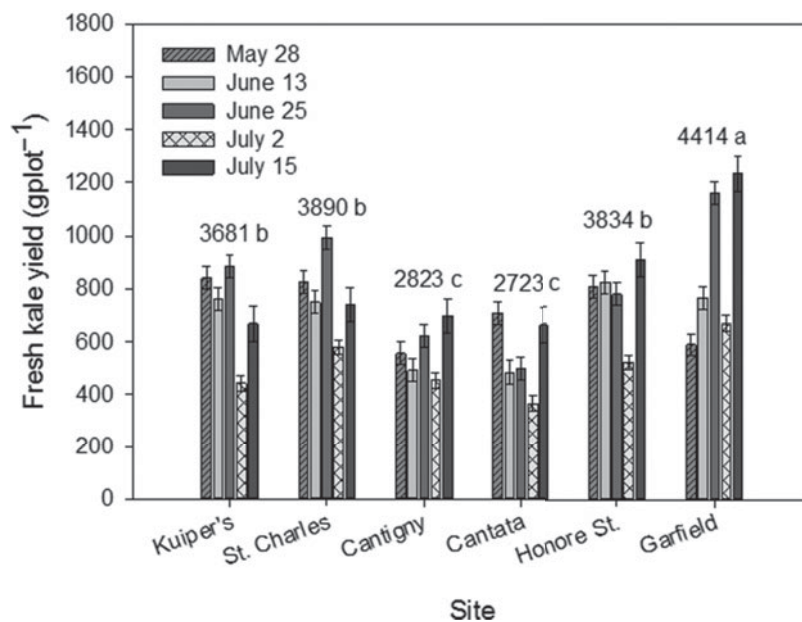


Figure 2. Fresh kale yield ($\text{gplot}^{-1} \pm$ one standard error) harvested across five dates at six sites across a rural (Kuiper's) to urban (Cantata, Honore St. and Garfield) latitudinal transect in the Chicago metropolitan region. Number above grouped vertical bars for each site is the sum of all yields and different letters indicate significant differences among sites ($\alpha = 0.05$).

at the Cantata site to 4414gplot^{-1} at Garfield, a difference of 38%. This result was somewhat surprising given that yield at the Garfield site during the first harvest interval was comparatively lower than most sites. Yield at the Garfield site during the second harvest interval was similar to Kuiper's, St. Charles and Honore St. sites, but yield during the third, fourth and fifth harvest intervals far exceeded all other sites (Fig. 2). Yield across all harvest intervals was consistently lowest at the Cantata and Cantigny sites (urban and peri-urban sites, respectively).

After analysis of preliminary environmental data, it was not immediately clear why kale yields were reduced at the Cantata and Cantigny sites. Differences in mean daytime solar radiation among sites appeared minor, but brief shading of at least one replicate block at both of these sites during dawn or dusk hours may be responsible for this negative yield response. A second pyranometer will be installed to quantify variability in light intensity gradients within sites that may be driving yield differences. If the 38% yield reduction can be attributed to partial light attenuation at these sites, this result would emphasize the importance and challenge of finding urban agriculture sites with access to full sunlight throughout the day and the need to develop shade-tolerant cultivars of vegetable crops for urban agriculture. Reductions in early yield of kale at the most urban site (despite the greatest final yield), may be related to elevated daytime ozone concentrations. Young plant seedlings may be more sensitive than juvenile and mature plants to elevated ozone concentrations³⁷. Indeed, interveinal leaf chlorosis typical of phytotoxic pollutant stress was observed during early kale growth at the Garfield site.

Relationships between kale yield (and other crops) and environmental measures are complex and will require several years of data and multivariate statistical models to understand and explain a portion of the variability among sites. Building a model to understand how microclimatic factors and atmospheric pollutants influence crop physiology and yield is the central aim of this project and results will provide a scientific basis for site, crop and cultivar selection for urban and peri-urban cropping systems. In the long term, results of this project will help to increase the profitability of urban food production in the North Central US—an outcome necessary for the sustained growth of the urban agriculture movement.

The supplementary materials for this article can be found at <http://www.journals.cambridge.org/raf>

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