THE ST. LOUIS OZONE GARDENS

Visualizing the Impact of a Changing Atmosphere

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In the presence of sunlight, some of the trace gases emitted by the combustion of fossil fuels react to form ozone (O_3), the primary component of photochemical smog. Thus, it is not surprising that levels of O_3 in the troposphere have more than doubled since the onset of the industrial revolution. The oxidant properties of O_3 make it toxic for most living things. Humans are susceptible to respiratory effects at today's ambient concentrations, and some common plants (including crops and trees) exhibit physiological damage and yield reductions at concentrations as low as 40 ppb. Today, background concentrations of O_3 continue to rise and are now above the threshold at which toxic effects can be observed in many plant species.

To educate the public on O_3 air pollution, we established the first St. Louis "Ozone Garden" near the Saint Louis Science Center (SLSC)'s James S. McDonnell Planetarium. The garden provides real-time measurements of O_3 concentrations as well as firsthand observations of the detrimental effects of this pollutant. Meteorological data, as well as the O_3 concentrations from the monitor, are recorded and publicly disseminated in near-real time via the Internet. Here we describe the project, its operations, and our goal to establish a network of these educational exhibits.

DAMAGE TO PLANTS. The most extensive research on crop loss due to O_3 was performed from 1980 to 1987 by the National Crop Loss Assessment Network (NCLAN). A. S. Heagle's 1989 paper summarizes these

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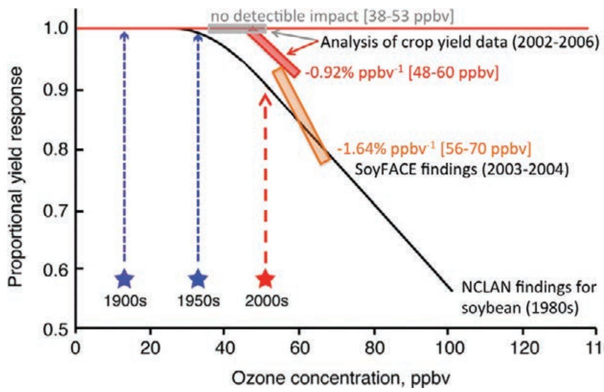

FIG. 1. Studies of proportional soybean crop loss conducted during the NCLAN Project are shown by the black curve. A subsequent crop yield loss study at the SoyFACE facility in Champaign, Illinois, is shown by the thick orange line. Results from the multivariate analysis of crop-yield data and surface O_3 data by Fishman et al. in 2010 *Atmospheric Environment* article are shown by the thick gray and red lines. The plot also shows the average background concentrations during the early twentieth century, middle twentieth century, and early twenty-first century.

studies, showing some plants (e.g., soybean, cotton, and peanut, which are dicotyledons, or plants with broad leaves) are more sensitive to yield loss caused by O_3 than other species (e.g., sorghum, field corn, and winter wheat, which are monocotyledons, or plants with narrow leaves, such as grasses). The impact of higher levels of O_3 on soybean yield is shown in Fig. 1 (findings from NCLAN and two subsequent studies). Furthermore, the observed O_3 trend in background concentrations (Fig. 2) in metropolitan St. Louis shows an increase of 7 ppb over the past 32 years. Such a trend is indicative of how O_3 has increased in nearby rural areas, where sensitive plants such as soybeans are grown. Thus, damage to sensitive plants should be observable over a typical growing season, either visually, or with respect to yield, or both.[1] In addition, according to Fig. 1, it is

[1] The value of the American soybean crop in 2012 was more than $40 billion, so even if yield is lowered by a few percent, the cost exceeds a few billion dollars annually, just for soybeans.

AN OZONE PARADOX

In many parts of the United States, emission controls on motor vehicles and power plants since the Clean Air Act of 1970 have decreased summertime O_3 concentrations in urban areas, according to the U.S. Environmental Protection Agency (EPA). Exceedance of the EPA O_3 pollution standard occurs when an 8-h average of values is greater than 75 ppb on any given day. Since 1999, EPA data show exceedances in the U.S. have been decreasing. The summer of 2012 in St. Louis was the warmest since 1936 and the warmest in the era of emission controls. The 8-h average exceeded 75 ppb at one or more of the eleven O_3 monitoring stations in the metropolitan area on 40 different days. These monitoring sites reported 170 exceedances, the most since 2007, but far less than what was commonplace before 2000.

While dirty urban air is getting cleaner, clean rural air is paradoxically getting dirtier, and can be illustrated by more than three decades of measurements in the St. Louis metropolitan area (Fig. 2). Cleaner air in Missouri, upwind of the city, has become dirtier at a rate of +0.24 ppb yr^{-1}. The trend for "dirty" air in this analysis is quite similar to the trend for exceedances reported by the EPA over the same period of time for St. Louis (in particular, see www.ewgateway.org/environment/aq/presentations/2012OzoneSeason-110212.pdf), while the trend for the "clean" air is consistent with the increase in O_3 concentrations that has continued through the first decade of the twenty-first century, as reported by Parrish et al. in an *Atmospheric Chemistry and Physics* article in 2012.

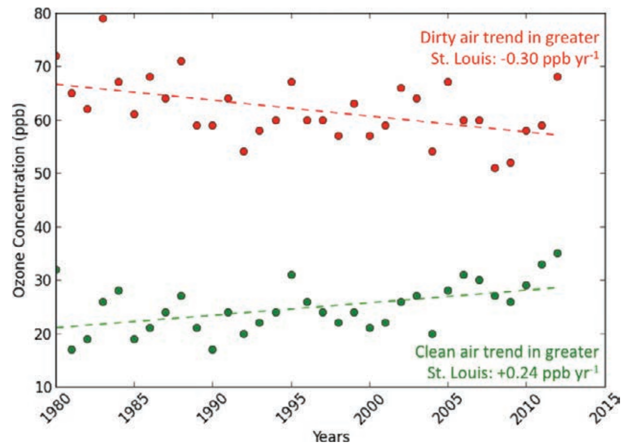

Fig. 2. Ozone trends between 1980 and 2012 in St. Louis for "dirty air" (red, influenced by local emissions) and "clean air" (green, representative of air entering the metropolitan area).

conceivable that no impact on crop yield would have been quantifiable until late in the twentieth century.

How ozone damages plants. Ozone is the most phytotoxic of all common air pollutants, and plant sensitivity and response to O_3 varies by species and plant population. After entering leaves through microscopic pores called stomata (singular: stoma), O_3 reacts with other molecules to form reactive oxygen species (ROS) and other toxic compounds. These compounds damage plants in a number of ways, including interfering with a plant's ability to produce and store food; making plants more susceptible to diseases and insect infestations; and reducing reproductive capabilities, which translates into yield decreases. Some plants are more sensitive to O_3 than others, and those that exhibit specific and unique O_3-induced symptoms, which allow visual detection and measurement of O_3 damage on leaves, are considered O_3 bio-indicator species.

THE OZONE GARDEN EXHIBITS. The St. Louis Ozone Garden concept is a featured activity within Saint Louis University (SLU)'s Center for Environmental Sciences (CES). Other such gardens have been planted elsewhere (e.g., Great Smoky Mountains National Park; www.nps.gov/grsm/naturescience/pk-homepage.htm), and we designed our garden using plants and techniques they have found successful. The layout for our garden was based upon Ladd et al.'s Ozone-Induced Foliar Injury Field Guide, which provides detailed instructions for planting an O_3 bio-indicator garden. This guide, readily available to the public (from NASA, online at http://science-edu.larc.nasa.gov/ozonegarden/materials-guide.php), introduces the concept of the Ozone Garden to groups interested in environmental education. Our first garden was officially opened to the public on 5 May 2012 at the SLSC in St. Louis's Forest Park. SLSC's Youth Exploring Science (YES) program, a science enrichment program for historically disadvantaged high school students, was incorporated into the educational aspect of this Ozone Garden. The YES students learned about ozone air pollution and its effects on plants, and gained experience conducting plant science research.

Maintaining the garden in 2012 was challenging because it was one of the hottest summers in St. Louis history. Despite the near-record heat and drought-like conditions, the perennial O_3-sensitive plants established their root systems in this irrigated garden. In 2013, in addition to the SLSC site, we started two other garden exhibits in the St. Louis metro area, one upwind at Grant's Farm, a popular family attraction in Affton, Missouri, and one downwind in Belleville, Illinois, at Southwestern Illinois College. We also expanded the network nationally through NASA's Air Quality Applications Science Team. In 2013, ozone gardens were started at the NASA Goddard Space Flight Center's Visitor Center in Greenbelt, Maryland; at Harvard University in Cambridge, Massachusetts, where an ozone garden was planted at their community garden site; and at the Virginia Living Museum in Newport News, Virginia, which is partnering with NASA's Langley Research Center. Progress on the expansion of the ozone garden network is updated on our website, located at www.slu.edu/department-of-earth-and-atmospheric-sciences-home/center-for-environmental-sciences/ozone-garden-home.

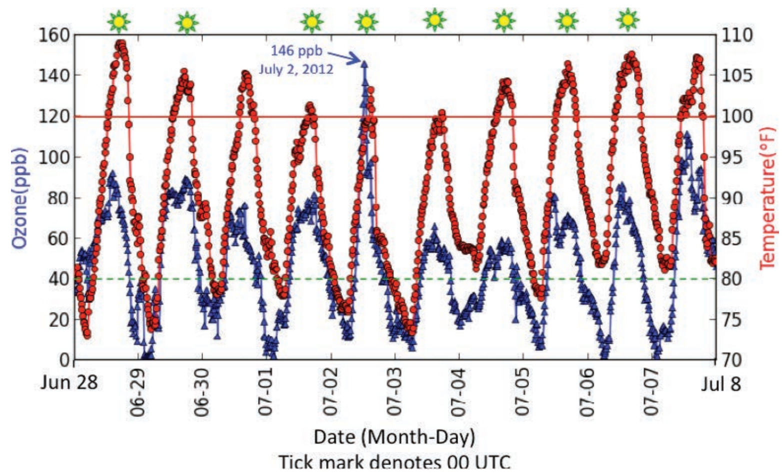

Fig. 3. A sample of the data from the GO3 Project website shows the continuous O_3 (blue triangles) and temperature (red circles) measurements between 0000 UTC 28 Jun and 0000 UTC 8 Jul 2012, one of the hottest periods on record in St. Louis. The red line marks temperatures of 100°F (37.8°C) and the green dashed line denotes O_3 concentrations >40 ppb, the threshold at which foliar O_3 damage begins. The "sun" marks over some of the curves indicate days of record-high temperatures recorded at STL National Weather Service sites. The reading on 28 Jun was 109°F (42.8°C) at the Ozone Garden and 108°F (42.2°C) at STL, the hottest reading ever for the month of June.

The perennial plants for the St. Louis gardens were started at the Missouri Botanical Garden greenhouses. Pennsylvania State University Emeritus Professor John Skelly provided seeds for the natural perennials common milkweed (*Asclepias syriaca)* and cutleaf coneflower (*Rudbeckia laciniata*). These seeds were originally collected by Skelly in Shenandoah National Park in Virginia from plants displaying symptoms of O_3 damage. Kent Burkey, USDA-ARS/North Carolina State University, provided snap bean (*Phaseolus vulgaris*) seeds of two cultivars: one O_3-sensitive and one O_3-tolerant. In addition, in 2013, Skelly provided us with O_3-sensitive potatoes (*Solanum tuberosum*), and Lisa Ainsworth of the USDA-ARS/University of Illinois donated O_3-sensitive and O_3-tolerant varieties of soybeans (*Glycine max*).

Ozone monitor and weather station. In 2012, O_3 and meteorological data were collected from the flagship garden at the SLSC from 21 May to 14 November. In 2013, data collection began on 24 April at the SLSC, and on 10 July at the second Ozone Garden at Grant's Farm; data from both sites are available through October 2013. A Davis Vantage Vue weather station (www.vantagevue.com/products/product.asp?pnum=06250) transmits temperature, humidity, pressure, rainfall, wind speed, and wind direction data with professional-level accuracy to an indoor receiver. The O_3 monitor, Model 202 from 2B Technologies (www.twobtech.com/model_202.htm), enables accurate and precise (±1.5 ppb) measurements of O_3 ranging from a few ppb to 100,000 ppb using UV absorbance at 254 nm. These data are also transmitted to a receiver and laptop computer indoors. Visitors to the garden can readily compare the current O_3 concentration displayed on the monitor in the garden to the forecasted range, posted on a sign.

As part of the GO3 Network (www.go3project.com), the O_3 and weather data are continuously uploaded to a website where they are available in real time and can be compared with other GO3 locations around the world. These measurements, with 15-min resolution, are available at http://go3project.com/network2/index.php/pages/ozone-data. During June, July, and August 2012, daytime O_3 levels recorded at the SLSC garden were consistently well above 40 ppb, the threshold for visible leaf damage in many O_3-sensitive plant species. For the summer of 2012, average daily maxima were generally between 70 and 80 ppb; on 7 days, peak 15-min values were more than 100 ppb. The highest concentration

VISUAL SYMPTOMS OF OZONE DAMAGE

The plants in the St. Louis Ozone Gardens come from seeds or cuttings of plants observed to display foliar O_3 damage symptoms. One of the questions we are often asked is, "How do you know the plant damage is from ozone, and not something else?" It is true that different plant species have varying responses to O_3 air pollution, ranging from the distinct symptoms seen in O_3 bio-indicator plants to general ill-health symptoms such as stunted growth and early yellowing in some plants. However, to answer this question, we explain the most typical symptoms of O_3-damaged leaves, which are seen most often and across many species, including crops, trees, and native plants.

Fig. SB1. Damage to common milkweed plant from (left) O_3, (center) mold, and (right) insects. Note how the underside of the plant (left panel, leaf in hand) exhibits no sign of foliar damage, a trait that makes O_3 damage easily identifiable in milkweed and many other plants.

According to Innes et al.'s *Guide to Ozone Induced Foliar Injury*, the most common symptoms of O_3-induced leaf injury, and those that appear on many of the plants in our gardens, are dark red, brown, or black flecking or "stippling," which is a result of plant cells producing anthocyanin pigments as an injury-defense mechanism. Stippling begins with a few small, angular shapes on leaves and can gradually progress, depending on the plant species and the amount of O_3 exposure, to prominent dark areas. Ozone injury symptoms do not appear on the veins of a leaf, and usually only occur on the upper leaf surface, leaving the lower leaf surface symptom-free. The symptoms are also usually more prominent on sun-exposed leaves.

Longer exposure to O_3 will cause increased damage so that older leaves of sensitive plants exhibit more advanced symptoms than younger leaves. As symptoms progress, leaves become increasingly chlorotic (yellow due to insufficient chlorophyll production) and necrotic (as cells die), and affected leaves often drop early from the plant. In a typical O_3-symptomatic plant, the stippling, chlorosis, and necrosis will progress from more severe in the older leaves near the bottom of the plant to less severe in the younger leaves near the top.

Ozone damage to milkweed (see Fig. SB1) can be readily identified because of the lack of damage present on the leaf veins and on the underside of the leaf. The top sides of the leaves display the characteristic dark stippling, while the leaf in the back is chlorotic and may soon drop. Ladd et al.'s field guide provides detailed explanations describing how O_3 damage can be distinguished from other types of damage on three different bio-indicator plants: common milkweed, cutleaf coneflower, and snap beans. As part of our education/outreach project, students monitor damage weekly on selected leaves and keep a record as the damage progresses.

of 146 ppb was measured during the middle of the prolonged record-setting 2012 heat wave in late June and early July (Fig. 3). This uniquely high concentration of O_3 over such a short time was also captured by three of the 11 O_3 monitoring sites in the St. Louis metropolitan area.

Observed O_3 damage. Foliar O_3 damage is identified and quantified using a visual scoring system developed by the U.S. National Park Service (NPS). Students working in the St. Louis Ozone Gardens are trained to identify and score O_3 leaf damage, which is based on percent damage per leaf area. A NPS O_3 scoring training module is available online (www.nature.nps.gov/air/edu/O3Training/index.cfm), and a detailed description of scoring O_3 bio-indicator plants is also available in Ladd et al.'s field guide. When O_3 damage is present in the Ozone Gardens, leaf damage scores are recorded weekly.

The first planting of snap beans in 2012 did not grow well due to both pests and nitrogen-deficient soil; these issues were rectified in a second snap bean planting in August (Fig. 4a, b). In addition to quantifying the observed foliar damage in the snap beans, we harvested the bean pods of the two cultivars in October and measured their dry weights. On average, the O_3-sensitive snap beans had a higher percentage of damaged leaves and the O_3-tolerant plants had higher average pod weights, indicating a higher yield in the tolerant plants (Fig. 5).

The extreme heat in 2012 likely caused slower than normal plant growth throughout the garden. In September, after the heat wave broke, mild foliar O_3 damage was observed in the common milkweed in the form of black stippling. According to Skelly, the provider of these seeds, the perennial species—common milkweed and cutleaf coneflower—often do not exhibit O_3 injury symptoms during the first year of planting. Indeed, in 2013, the first-year plantings of these perennials in the two new gardens did not display O_3 damage. During summer 2013, on the other hand, O_3 foliar damage on both the common milkweed and the cutleaf coneflower in their second season at the SLSC garden was widespread, despite much lower O_3 concentrations than those measured the previous year (see Figs. 4c, d). Both of these species provided an excellent educational exhibit at the SLSC in 2013.

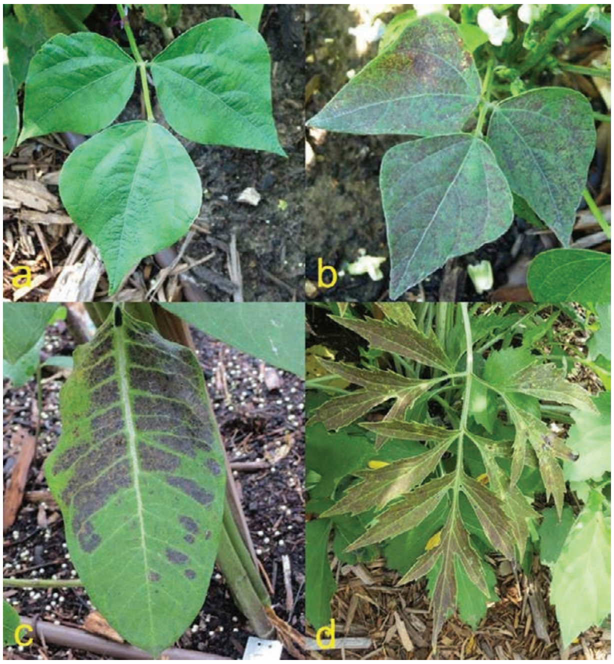

Fig. 4. Differences between the (a) O_3-tolerant snap beans and (b) the sensitive snap beans are readily seen in these two photographs taken in Sep 2012. Foliar damage (black spots) on (c) common milkweed and (d) cutleaf coneflower observed in Aug 2013.

OUTREACH VALUE AND FUTURE PLANS.

The Ozone Garden at the SLSC is highly visible near the entrance of the James S. McDonnell Planetarium. About 900,000 visitors attend the SLSC annually, and ~40% of them enter and leave through the planetarium. The garden itself is adjacent to a walking, running, and biking path in Forest Park, a 1,371-acre city park. Thus, casual visitors happen upon this Ozone Garden with no initial intent of learning more about science.

According to Susannah Fuchs, senior director of Environmental Health for the American Lung Association, Plains-Gulf region,

> The Ozone Garden is a great part of the toolkit that we use for ground-level O_3 outreach and education through the St. Louis Regional Clean Air Partnership, and also for our own independent air pollution and lung health outreach. It's very helpful to have something so totally visible and three-dimensional to which we can refer people. The plants and simple signs speak to people at least as clearly and much more succinctly than a brochure about air pollution and human health does.

The observations gathered informally over the first two growing seasons at the Ozone Garden will aid in the formulation of a new, much more expansive, SLSC exhibit. The new Ozone Garden will be included in a larger, permanent exhibition at the SLSC's main building. This new exhibition, currently in development, focuses on agriculture and how science, technology, and global change influence the efficiency of food production. Being a more integral part of the SLSC— a popular destination for school field trips—we envisage establishing an educational and interactive exhibit modeled after the class trips to the ozone garden at the Appalachian Highlands Science Learning Center (www.nps.gov/grsm/naturescience/environmentalfactors.htm). Students would learn about O_3 air pollution in more depth and, in the summer and fall, help collect the O_3-induced leaf damage data.

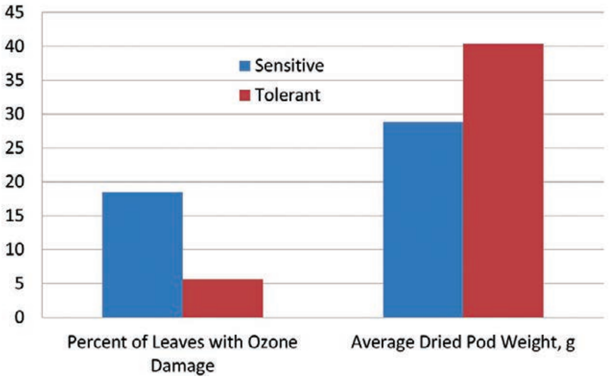

Fig. 5. Graph illustrating the difference between the percentage of leaves with O_3 damage and the bean pod dry weight from O_3-sensitive and tolerant snap beans grown in Aug–Oct 2012 at the SLSC St. Louis Ozone Garden.

This exhibition is anticipated to open in 2016. The SLSC and SLU will continue to collaborate to develop school programs and teacher workshops for the Ozone Garden in its new location. In addition, the SLSC will conduct structured evaluations of visitor engagement and interaction with the exhibit, and measure learning outcomes and their alignment with STEM education standards.

The Franklin Institute in Philadelphia, Pennsylvania, plans to replicate the St. Louis Ozone Garden model in its outdoor Science Park. The Franklin Institute Ozone Garden will open in 2014 and will primarily engage high school students. A project-based curriculum involving the garden will focus on global change, plant biology, atmospheric science, and experimental research methods. The Franklin Institute will also partner with scientists from Drexel University to expose students to research and analysis. The Institute also plans to install another Ozone Garden on the roof of the new Nicholas and Athena Karabots Pavilion, a 53,000-square-foot building addition.

In summary, the Ozone Gardens are being adopted by science museum venues around the country. The goal is to establish a network of these exhibits to help explain global change to the public in a tangible manner.

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