

**Field Surveys to Assess Foliar Ozone Injury on Plants in National Parks
and Monuments on the Colorado Plateau**

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BACKGROUND

Tropospheric, or ground-level, ozone of anthropogenic origin is recognized as one of the most widely dispersed and phytotoxic air pollutants in the United States, and its effects on the physiology, growth, productivity and wellbeing of plant species have been widely researched and documented in laboratory and field studies (EPA 1996, 2007). Ozone is not emitted by any source, but produced by photochemical reactions in the atmosphere that are powered by sunlight and involve volatile organic compounds (VOC) and oxides of nitrogen (NO_x). Precursor pollutants are released in urban and industrialized areas and from energy development in rural locations, and the generated ozone can be transported hundreds of miles downwind producing deleterious impacts on agricultural crops and native plant communities along its path of movement (EPA 2001).

Long-distance transport of ozone is observed in the eastern United States in the summer when the offshore Bermuda High moves air northeastward from Washington, Baltimore, Philadelphia, New York and Boston. As polluted urban air moves through this conurbation, ozone is produced and accumulates so that some of the highest levels of ozone in the east occur on Cape Cod. Then the air moves across the Gulf of Maine to make landfall at Acadia National Park in Maine. Acadia's remote location might lead one to suppose it possesses clean air, but ozone levels there can approach and have exceeded the EPA secondary ambient air quality standard. Research and field assessments conducted at Acadia documented the presence of ozone injury on sensitive plants in the park (Eckert et al. 1999).

Wherever hydrofracking for natural gas has been conducted in the western United States there have been significant increases in ambient levels of ozone. Oil and gas drilling in Wyoming has resulted in elevated concentrations of ambient ozone in remote areas that previously had low background levels of the pollutant (Wyoming Department of Environmental Quality 2010). In the Jonah gas field in Wyoming, an area with pristine air quality before hydrofracking commenced, ambient ozone concentrations now approach levels that violate the Federal ambient air quality standard. As reported in the September 5, 2011 issue of High Country news, ozone levels in gas fields in rural Utah's Uintah Basin surpassed federal limits 26 times in the first three months of 2011. Hydrofracking in the Barnett Shale formation in Texas is considered to be an important contributor to increases in ozone that violated Federal air quality standards in the Dallas/Fort worth area.

Although the Rocky Mountain west experiences elevated levels of ozone from both urban and rural sources, efforts to assess what effects the pollutant may be having on native vegetation in the region's national parks have been limited. From 2006 through 2010, assessments were conducted in Rocky Mountain National Park to determine whether ozone was producing foliar injury on plants there (Kohut et al. 2012). Cutleaf coneflower (*Rudbeckia laciniata* var. *ampla*), spreading dogbane (*Apocynum androsaemifolium*) and quaking aspen (*Populus tremuloides*) were assessed each year. These species were selected because they are bioindicators for ozone; bioindicator species are highly

sensitive to ozone and produce foliar injury symptoms and patterns that are diagnostic for the pollutant. Foliar injury in the form of ozone stipple was found on coneflower each of the five years. The incidence of injured plants on sites with injury ranged from 5 to 100%. The severity of injury on affected foliage was generally less than 4%, but occurred on some leaves at a level greater than 12% in three years and in one year on one plant at a level greater than 75%. No foliar ozone injury was found on spreading dogbane or quaking aspen in any year of the survey.

While all three species examined in Rocky Mountain National Park are considered to be highly sensitive to ozone, cutleaf coneflower was found on wet or riparian habitats while quaking aspen and spreading dogbane were found on more mesic and dry sites. Access to greater levels of soil moisture throughout the growing season likely allowed cutleaf coneflower to avoid drought stress and maintain higher levels of gas exchange and ozone uptake during the hotter periods of summer when ozone levels are often the highest. In a follow-up field survey in 2012 when precipitation was greatly reduced, foliar ozone injury was still observed on coneflower plants along streams and on damp sites.

The foliar injury on cutleaf coneflower at Rocky Mountain National Park was the first documentation of ozone injury in the park and in the Rocky Mountain region. Its presence raises the question of whether plants on riparian and wet sites in other parks experiencing elevated levels of ozone are also being injured. Desert parks have not been surveyed for ozone injury because generally low soil moisture is assumed to restrict transpiration and therefore gas exchange and the uptake of ozone. Fracking for oil and gas in Utah, Colorado and New Mexico raises the possibility that elevated levels of ozone may be producing foliar injury on plants in near-by national parks and monuments on the Colorado Plateau. To address this concern, field assessments were conducted in 2016 in selected parks and monuments downwind of active oil and gas shale plays to determine whether the levels of ozone occurring in them were producing foliar injury on ozone-sensitive species of plants.

Triad Concept of Ozone Pathology

Foliar ozone injury is produced on plants when a triad of biological and environmental variables are satisfied: the levels of ozone exposure exceed a threshold for foliar injury, plant species sensitive to ozone are present, and environmental conditions occur that facilitate the uptake of ozone by the plants. Foliar injury is produced when specific properties of each element of the triad of variables are satisfied, and the interactions of the variables promote the effects of the exposure. The triad concept of injury is presented in the Handbook for the Assessment of Foliar Ozone Injury on Vegetation in the National Parks (Kohut 2007). Since it serves as the framework for the preparatory tasks in the study and the subsequent field assessments, it is discussed in more detail below.

First, the ambient level of ozone exposure must exceed the threshold required for injury. Ozone monitoring stations in or near the park provide the best indications of the levels of exposure plants receive. However, it is important to recognize that ozone exposure

concentrations at a specific field site can vary significantly from those at a nearby monitoring station depending upon elevation, aspect, and openness of the site.

Second, the plant species exposed must be genetically predisposed to be sensitive to ozone. Differences in genetic disposition to ozone are most evident at the species level, but significant differences in sensitivity are also manifest among clonal lines and individuals within a species. Classifications of the sensitivity of various plant species to ozone are reflections of fundamental differences in responses that have been observed in laboratory and field research using controlled ozone exposures and in subsequent observations of foliar ozone injury in the field.

Lastly, the plant in the field must experience environmental conditions that foster the uptake of ozone from the atmosphere. Environmental conditions that favor photosynthesis will promote gas exchange and the uptake of ozone along with carbon dioxide. However, low levels of soil moisture and high temperatures can lead to stomatal closure in plants, and thereby significantly reduce the uptake of ozone. The high temperatures and intense sunlight that foster the production of ozone can also be associated with reduced precipitation. Consequently, low soil moisture and elevated temperatures often occur when ozone concentrations are high. This can create a situation in which ambient levels of ozone are above the threshold for plant response, but reduced rates of gas exchange effectively exclude ozone from the interior of the plant leaf. Under these circumstances, the effective exposure dose is considerably less than that in the ambient atmosphere. It is important to remember, however, that within a generally adverse soil moisture environment at a park, soil moisture levels more favorable for pollutant uptake can exist at the site level. Under these conditions, plants on favorable microsites may express foliar ozone injury while adjacent plants do not.

Showman (1991) documented the importance of soil moisture in regulating the response of bioindicator species to ozone in the field. In 1988 and 1989 he assessed foliar ozone injury on up to seven bioindicator species on 13 permanent sites in Indiana and on 11 sites in Ohio. In 1988, ambient levels of ozone at nearby monitoring sites showed up to 63 hours of concentrations above 120 ppb while precipitation in the area was 5.6 inches below average. In 1989, ozone levels at the same monitoring sites exceeded 120 ppb for only 2 hours while precipitation was 8.7 inches above average. In 1988, the year of higher ozone exposure and drier conditions, ozone injury was observed only on common milkweed on one site in Indiana and two sites in Ohio while all other bioindicator species remained uninjured. In contrast, in 1989, the year of lower ozone exposure and wetter conditions, injury was observed on common milkweed on 11 of 13 sites in Indiana and on all 11 sites in Ohio. In addition, injury was also found on blackberry, sweet gum, tulip poplar and wild grape in Indiana, and on white ash, wild grape and blackberry in Ohio. These observations illustrate the importance of soil moisture in regulating the potential effects of ambient levels of ozone by influencing stomatal opening, the exchange of gases with the atmosphere and the concomitant uptake of ozone.

Production of foliar ozone injury is greatest when all variables of the response triad are optimized. Maximum foliar injury occurs when a particularly sensitive plant species or

genotype is exposed to concentrations of ozone above the injury threshold under environmental conditions that foster pollutant uptake. Movement of any of the three variables away from the optimum will reduce the level of injury produced. Significant movement of any variable away from the optimum can preclude the production of injury, no matter how favorable the other variables may be.

METHODS

Assessments were conducted at Arches National Park (ARCH), Canyonlands National Park (CANY), Colorado National Monument (COLM), Dinosaur National Monument (DINO) and Mesa Verde National Park (MEVE) located in the eastern portion of the Colorado Plateau in Utah and Colorado (Figure 1). The potential for foliar ozone injury in each park was assessed by determining whether the levels of ozone exposure were high enough to produce foliar injury, whether species of plants known to be bioindicators for ozone could be found in the parks, and whether the parks had riparian or moist habitats in which the plants might be found. It was also essential that National Park Service staff at the park be willing and able to commit time to participate in the field assessments. Their participation allowed plants to be readily and correctly identified and assessment sites to be efficiently located.

Characterizing Levels of Ozone Exposure

Ozone monitoring data from CANY, COLM, DINO and MEVE were analyzed to calculate indices of exposure to determine whether levels were high enough to produce foliar injury on ozone bioindicator and sensitive plant species. Ozone is not monitored at ARCH so data from nearby CANY were used as a surrogate. Exposures were characterized using the Sum06, W126- 7month and W126-3 month cumulative indices, and the numbers of hours at or above 60 ppb, 80 ppb and 100 ppb (N-values). The W126-3 month index was proposed by the EPA in 2010 as a revised secondary ozone National Ambient Air Quality Standard to protect vegetation (EPA 2010).

Sum06. The Sum06 index is the 90-day maximum sum of the 12 one-hour (0800 through 1959) concentrations of ozone $\geq$ 60 ppb (0.06 ppm) (Heck and Cowling 1997). The index is calculated over running 90-day periods and the maximum sum can occur over any period of the year, although the seasonal pattern of ozone generation usually results in it occurring over the summer months.

Injury thresholds for the Sum06 index in cumulative ppm-hr are:

Natural Ecosystems	8 - 12 ppm-hr (foliar injury)
Tree Seedlings	10 - 16 ppm-hr (1-2% reduction in growth)
Crops	15 - 20 ppm-hr (10% reduction in 25-35% of crops)

W126-7 mo. The W126-7 mo index is the weighted sum of the 24 one-hour ozone concentrations daily from April through October, and the number of hours of exposure to

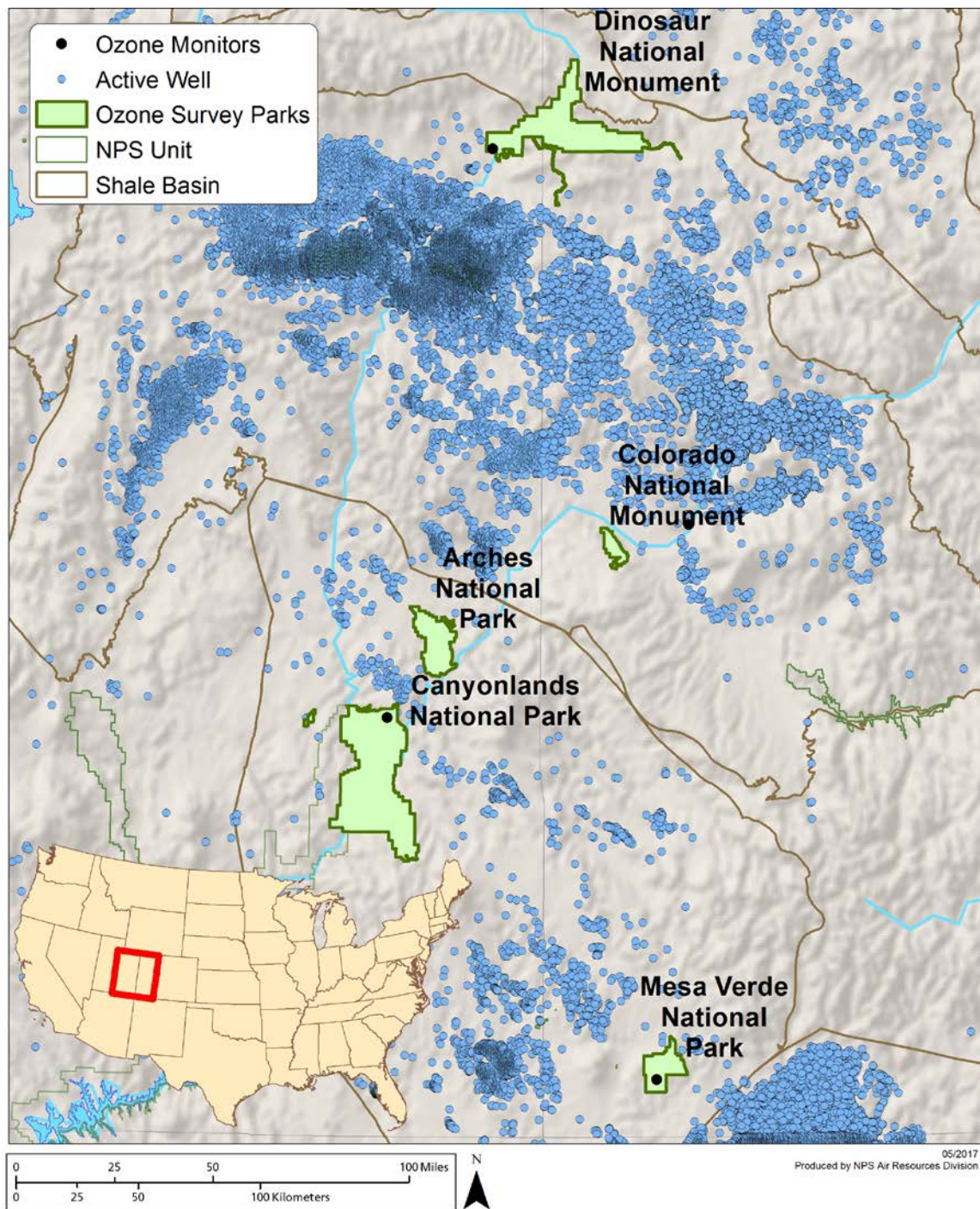


Figure 1. Parks on the Colorado Plateau where plants were assessed for foliar ozone injury in August 2016. Locations of ozone monitoring sites and active wells in fracking areas are also depicted.

concentrations ≥ 100 ppb (0.10 ppm) during that period (Lefohn and Runeckles 1987, Lefohn et al. 1988). The W126-7 mo index uses a sigmoidal weighting function in producing the sum: the lower concentrations are given less weight than are the higher concentrations since the higher exposures play a greater role in producing injury. The significance of the higher concentrations is also reflected in the requirement that there be a specified minimum number of hours of exposure to concentrations ≥ 100 ppb. Thus, the W126-7 mo index has two criteria that must be attained to satisfy its thresholds: a minimum sum of weighted concentrations and a minimum number of hours ≥ 100 ppb.

Injury thresholds for the W126-7 mo index in cumulative ppm-hr and numbers of hours are:

	W126-7 mo	N100
Highly Sensitive Species	5.9 ppm-hr	6
Moderately Sensitive Species	23.8 ppm-hr	51
Low Sensitivity	66.6 ppm-hr	135

W126-3 mo. Exposures were also calculated in the form of the secondary standard proposed in EPA's 2010 Federal Register Notice on the ambient air quality standards for ozone (EPA 2010). The W126-3 mo index is the running maximum 3-month, cumulative 12 one-hour (0800-1959) W126 weighted value.

Injury thresholds for the W126-3 mo index in cumulative ppm-hr are:

Foliar injury in natural ecosystems	5 - 9 ppm-hr (foliar injury)
Growth reductions	
Tree Seedlings in natural ecosystems	7 - 13 ppm-hr
Tree seedlings/saplings in plantations	9 - 14 ppm-hr

While EPA proposed a W126-3 mo standard in the range of 7-15 ppm-hr to protect vegetation, the threshold it identified for foliar injury is 5-9 ppm-hr.

N-values. N-values, the numbers of hours of exposure each year that equaled or exceeded 60, 80 and 100 ppb, were also determined. While there are no injury thresholds associated with the values by themselves, they provide insight to the frequency of high ozone exposures and the N100 value is used in conjunction with the W126-7 mo index.

Selecting Plant Species to Examine

Plant species display a wide range of sensitivity to ozone ranging from those very sensitive and readily injured to those resistant to high levels of exposure. Ozone bioindicator species are highly sensitive and express foliar injury at ambient levels slightly above background. Species considered intermediate in sensitivity are injured by exposure to moderately elevated levels of ozone. Most species of plants are relatively resistant to ozone and able to withstand extended periods of exposure to elevated levels without the development of foliar injury.

Research conducted in the laboratory or field employing controlled levels of ozone exposure provides information on the relative ozone sensitivity of plant species, the nature of the foliar injury produced and the level of exposure required to produce injury. These studies provide primary guidance to the relative ozone-sensitivity of the plant species evaluated and are used to identify bioindicator and sensitive species. Care must be exercised in assessing the research findings since some studies use ozone exposure regimes that do not mimic the concentrations, frequencies or dynamics of exposures occurring in nature and thus their findings regarding the ozone-sensitivity of plant species and the nature of the symptoms produced are subject to question.

As indicated previously, bioindicator species are highly sensitive to ozone and produce foliar injury symptoms and patterns that are diagnostic for the pollutant. The foliar symptoms are unique in appearance and distinguishable from injury produced by other stresses. The nature of the markings, their distribution on the plant and the general levels of exposure at which they occur have been confirmed by controlled ozone exposures. To be most useful, bioindicator species should be readily identifiable and widely distributed in the area to be surveyed for injury.

Foliar injury on bioindicator species in the field indicates that ozone exposures are elevated, are affecting sensitive species of plants, and may be reaching levels harmful to plants of intermediate sensitivity. Although bioindicator species are highly sensitive to ozone, genetic differences among individual plants result in variations in sensitivity that may be expressed as differences in the degree of foliar injury among plants in a population. One should not expect uniform levels of injury among bioindicator plants of the same species on an assessment plot.

The environmental component in the triad of factors leading to the production of foliar ozone injury operates on both large and small scales. While large-scale precipitation data for a park indicate soil moisture conditions may be restricting the uptake of ozone, site-specific soil moisture conditions can be quite different. Bioindicator species that occur in riparian or more moist habitats may continue to exchange gases with the atmosphere while soil moisture conditions in the broader environment are less favorable. Similarly, while bioindicator plants found on dryer sites may be uninjured, plants growing on more moist sites within the greater habitat may be affected.

Ozone bioindicator species are the first plants to be examined for foliar ozone injury in the field. The ozone bioindicator species for each park were selected by comparing the floral lists for the park with a list of bioindicator species found in that region. The primary source of ozone bioindicator species to be used in the study was the list compiled by the National Park Service at a meeting of experienced ozone field researchers in Baltimore in 2003 (Porter 2003). Additions to the list were drawn from a review of research publications subsequent to 2003 that confirmed the ozone-sensitivity of a species through controlled ozone exposure and provide information on the level of exposure at which injury was produced. The artificial nature of some of the ozone

exposure regimes employed in several of the research publications precluded application of the results to conditions in the field.

Once a list of candidate bioindicator species was compiled for a park, National Park Service plant specialists in that park were contacted to confirm the presence of the species there, provide information on the abundance of the species and indicate the types of habitat(s) in which it may be found. Primary attention was directed toward bioindicators found in riparian and moist habitats, but species found on mesic sites were also considered.

Relatively little is known about the ozone-sensitivity of the vast majority of plant species found on the Colorado Plateau. This is a consequence of most ozone exposure research having been conducted in the Northeast, Midwest, Southeast and the Far West and using plant species common to those regions. Very little research has been conducted in the Rocky Mountain and Southwest regions and with plants found there. Consequently, it was decided to also examine foliage of species other than bioindicators as they were opportunistically encountered in the field. Since the ozone sensitivity and nature of foliar injury on these species are unknown, the etiology of any ozone-like markings on them would be uncertain. However, finding ozone-like injury on any of these species could potentially serve to spur controlled ozone exposure research with species from the Colorado Plateau region.

Plant specialists at each park were asked to participate in the field surveys to both help find and identify the bioindicator species and to gain experience in identifying foliar ozone injury. Participation of park staff in the assessments was essential to the success of the effort. The staff person needed to be committed to the field study for the duration of the visit. Without such support from the park, time spent there would not be used very efficiently and collection of injury information compromised. In the field, the staff person learned how to assess plants for foliar ozone injury and examined photographs of what ozone injury looks like. In subsequent years the staff person will be able to look for foliar ozone injury when in the field and thereby provide the park with a first level of ozone injury assessment.

Quantifying Precipitation

An assessment of soil moisture status is important in evaluating the potential for previous and current ozone exposures to produce foliar injury. While ambient ozone monitoring data are accurate and abundant, measuring soil moisture content directly is not feasible for this study. Thus, by necessity, bulk precipitation measurements are used as a surrogate for soil moisture. There are, however, several factors that make precipitation a less than ideal indicator of soil moisture, particularly for the period of summer ozone exposure.

At the end of summer on the Colorado Plateau, soil moisture is low due to uptake by plants, evaporation due to heating the soil, and the lack of replenishment. Precipitation in the parks is generally in the form of winter rain and snow and late

summer monsoon rainstorms. Between these two periods there is an arid season, approximately May through July, when soil moisture reaches its lowest level. This is also the period of highest ozone exposure. Soil moisture status during the summer months is best approximated by summing precipitation for the water year, a period that runs from October through September. The water year attempts to capture the influences of the gentle fall and winter rain and snow melt that percolate into the soil and are important sources of ground water recharge prior to the summer arid period. The summer monsoon rains of August and September are intense and produce mainly runoff with modest recharge of soil moisture. Thus, all precipitation data in this report are for the water year of October through September.

Foliar Ozone Injury Assessment

Foliar ozone injury was assessed using a scouting approach (Kohut 2007). In a scouting assessment, bioindicator plants are examined as they are encountered on the assessment sites in the field. The assessment provides a yes/no answer with regard to the presence of foliar injury in the park. It requires the smallest investment of time, personnel and funds, but because it is not quantitative it provides limited information on the incidence, severity, and spatial distribution of injury. Scouting is a good first effort for a park since it locates bioindicator plants, establishes potential assessment plots, and provides experience for the park staff in identifying foliar ozone injury. If a scouting survey is the only assessment a park can conduct, it should do so since the confirmation of foliar ozone injury has management and regulatory implications. A scouting assessment can be employed over a series of years to document the presence or absence of foliar injury over time. If foliar injury is found and quantitative information on its incidence and severity is desired, a survey assessment approach can be adopted (Kohut 2007).

Foliar injury commonly produced by ozone includes stipple, fleck, and bifacial necrosis (Skelly et al. 1987, Flagler 1998, Innes et al. 2001, Kohut 2007). Stipple is the most common form of ozone injury and is characterized by the appearance of interveinal, dot-like areas of tan, red, brown, purple, or black pigmentation on only the upper surface of the leaf. Stipple can be either distributed over the surface of the leaf or concentrated in certain areas. It may range from widely scattered dots to those whose density provides uniform coloration to all or part of the leaf surface. Coloration, density, and distribution of stipple are functions of plant species and the duration and nature of exposure. Stipple is a highly diagnostic form of ozone injury.

Fleck is characterized by small, discrete areas of dead tissue visible only on the upper surface of the leaf. Fleck is produced by the death of cells in the palisade mesophyll of the leaf. The lesions may be irregular in shape and range in color from tan to black. Bifacial necrosis is a more severe form of injury resulting from cell death in both the palisade and spongy mesophyll and epidermal tissues of the leaf. Injury appears on both sides of the leaf and dead tissue may take on a papery texture. Coloration in bifacial necrosis can range from light tan to black. Fleck and bifacial necrosis are not highly diagnostic form of ozone injury, but their distribution on individual leaves and over the plant helps in making a diagnosis.

Schedule

The field assessment of foliar injury was conducted on August 8-18, 2016. The survey was performed at this time to allow the plants to receive a full growing season of exposure to ozone, but before drought or seasonal change initiated foliar senescence. Surveys were conducted in parks in the following sequence: Colorado National Monument, (COLM) Dinosaur National Monument (DINO), Arches National Park (ARCH), Canyonlands National Park (CANY) and Mesa Verde National Park (MEVE) with a maximum of two days spent in the field in each park.

FIELD SURVEYS AND RESULTS

Arches National Park (ARCH)

NPS Staff Support

NPS staff members Matt Van Scoyoc and Rebecca Weissinger supported the field survey at Arches National Park (ARCH). Their assistance in the field allowed us to efficiently travel to sites where bioindicator and sensitive plant species were located, and directed us to watercourse and moist habitats where additional plant species could be examined. Rebecca provided valuable expertise as a field botanist and was particularly helpful in locating hanging gardens with a variety of plants to examine. The field assessment at ARCH was conducted on August 11-12, 2016.

Ozone Exposure and Precipitation

Ambient ozone is not monitored at ARCH therefore data from nearby Canyonlands National Park (CANY) was used to approximate exposures at ARCH. The data were used to calculate ozone exposure indices for the past 11 years including 2016 (Table 1). The ozone data show moderately high levels of exposure from 2006 through 2016. The W126-7mo exposure summation significantly exceeded the criterion of 5.9 ppm-hr each year, however there were no years in which the second index criterion of 6 hours over 100 ppb was satisfied. Consequently, the overall W126-7mo exposure index threshold was not attained in any year. The W126-3mo index exceeded the 5 to 9 ppm-hr threshold each of the past 11 years. The Sum06 index threshold of 8 to 12 ppm-hr was exceeded in 10 of the years, but not in 2016. Overall, the levels of ozone exposure have been decreasing over the past 3 years as is apparent in the W126 3-mo, Sum06 and N60 values.

The N-values indicate that exposure to concentrations greater than 60 ppb was between 414 and 875 hours between 2006 and 2013, but significantly lower the last 3 years with 186 hours in 2016. Most years had 3 or fewer hours greater than 80 ppb, with a maximum of 8 hours in 2012, and no hours exceeded 100 ppb in the 11 years of assessment.

Precipitation for ARCH was based on values for CANY and ranged from 139 mm to 296 mm over the past 11 years with an average of 217 mm. In 2016 there was 247 mm of precipitation.

The ozone exposure indices and N-values for 2016 indicate it was a year of low ozone exposure at ARCH. The W126 3-mo value of 8.7 ppm-hr, Sum06 value of 6.4 ppm-hr and N60 value of 186 hours were the lowest in the 11 years of data compiled. The 247 mm of precipitation was slightly above the 11-year average.

Ozone Bioindicator and Sensitive Plant Species

Comparison of the floral list for ARCH with the list of plant species known to be bioindicators for or sensitive to ozone indicated there were potentially 2 bioindicator and 5 sensitive species to be found in the park (Table 2). These species were emphasized in the search for foliar ozone injury. Due to the lack of research information about the ozone sensitivity of the vast majority of plants found on the Colorado Plateau and at ARCH, it was decided to also examine the foliage of other species opportunistically encountered in the field.

Field Survey Locations, Plant Species Examined and Results

Plants were assessed for foliar ozone injury at 9 sites at ARCH with between 3 and 17 species examined at each site (Table 3). The only ozone bioindicator species found and examined was *Rhus aromatica* (fragrant sumac). Some of the locations visited were streamside or near standing water where soil moisture may have been a somewhat less significant constraint to gas exchange by the plants. Plants in hanging garden communities were also examined.

No foliar ozone injury was observed at ARCH. *Rhus aromatica* was examined on 3 sites and found to be uninjured. As indicated previously, the level of ozone exposure at ARCH in 2016 was the lowest of the previous 11 years and precipitation slightly above average. Collectively, this set of conditions did not favor the production of foliar injury on even bioindicator species.

Conclusions

The levels of ambient ozone at ARCH have historically exceeded injury thresholds by significant margins. Those levels were high enough to produce foliar injury if plants were actively exchanging gases with the atmosphere. Thus, soil moisture is a critical factor influencing the production of foliar ozone injury at ARCH. Records indicate that levels of precipitation in some past years with high levels of ozone were up to 20% greater than that received in 2016 and 36% greater than average. The ozone and precipitation histories suggest that conditions favorable for the production of foliar injury on highly sensitive plants can be present at ARCH. However, the low level of ozone exposure and more average precipitation in 2016 did not favor the development of foliar injury.

Given the historical exposure and precipitation data and the nature of some of the sites visited at ARCH, it seems reasonable to consider conducting assessments for foliar injury in selected years in the future. Several of the sites along Courthouse Wash exhibited either standing or flowing water or likely had subsurface water that could be accessed by plants. Sites along or near Freshwater Canyon, including hanging gardens, also have access to water and may be favorable for future assessments. Similar watercourses or hanging gardens within ARCH, particularly ones known or believed to contain plant species sensitive to ozone, should be considered for assessment in years when the levels

of ozone exposure and precipitation suggest conditions are favorable for the development of foliar injury.

Table 1. Ozone exposure indices for Arches National Park (approximated by monitoring data from nearby Canyonlands National Park) for 2006 through 2016. Precipitation data are also provided for each year. Units: W126-7mo, W126-3mo and Sum06 are ppm-hr; N-values are number of hours; precipitation in mm for the Oct - Sept water year. Exposure indices in bold exceed the injury threshold.

Year	W126-7 mo*	W126-3 mo*	3 mo period	Sum 06*	N60	N80	N100	Precip
2006	28.3	17.6	May - Jul	27.6	791	0	0	163
2007	29.2	16.5	May - Jul	23.4	875	1	0	217
2008	27.5	16.6	Apr - Jun	24.4	747	2	0	202
2009	22.4	11.7	Mar - May	10.8	445	0	0	139
2010	20.5	12.8	Apr - Jun	15.5	499	3	0	215
2011	23.1	13.2	May - Jul	15.3	571	1	0	271
2012	27.8	15.7	May - Jul	21.9	832	8	0	185
2013	21.4	12.3	Apr - Jun	15.3	414	0	0	179
2014	17.1	10.3	Apr - Jun	8.0	242	0	0	268
2015	15.9	10.3	Apr - Jun	9.5	277	0	0	296
2016	14.8	8.7	May-Jul	6.4	186	0	0	247

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

Table 2. Ozone bioindicator and sensitive species at Arches National Park. Bioindicator species are in bold type.

<u>Scientific Name</u>	<u>Common Name</u>	<u>Bioindicator</u>
<i>Apocynum cannabinum</i>	Indian hemp	no
<i>Mentzelia albicaulis</i>	white-stemmed evening-star	yes
<i>Poa pratensis</i>	Kentucky bluegrass	no
<i>Rhus aromatica</i> var. <i>aromatica</i>	fragrant sumac	yes
<i>Robinia pseudoacacia</i>	black locust	no
<i>Salix exigua</i> var. <i>exigua</i>	coyote willow	no
<i>Salix gooddingii</i>	Goodding's willow	no

Table 3. Locations visited and plant species assessed in field survey for foliar ozone injury at Arches National Park August 11-12, 2016. Bioindicator species are in bold type.

Visitor Center

Apocynum cannabinum
Grindelia fastigata
Oenothera longissima

Salix spp.
Salix exigua
Xanthium strumarium

Salt Wash / Fresh Water Canyon

Moab Boat Ramp

Bassia hyssopifolia
Salix exigua
Salix gooddingii

Apocynum cannabinum
Artemisia tridentata
Celtis reticulata
Chenopodium spp.
Chrysothamnus viscidifloras
Euthamia occidentalis
Fraxinus anomala
Grindelia fastigata
Hymenoxys-like
Oenothera longissima
Populus angustifolia x *P. fremontii*
Quercus gambelii
Rhus aromatica
Salix eriocephala
Solidago missouriensis
Thelypodium integrifolium
Xanthium strumarium

Lower Courthouse Wash

Asclepias speciosa
Clematis ligusticifolia
Grindelia fastigata
Populus fremontii
Rhus spp.
Rhus aromatica
Salix exigua
Salix gooddingii
Xanthium strumarium

Middle Courthouse Wash – below bridge

Asclepias speciosa
Grindelia fastigata
Melilotus officinalis
Populus fremontii
Rhus aromatica
Salix spp.
Salix exigua
Xanthium strumarium

Fresh Water Canyon 2 – hanging garden

Aquilegia micrantha -- endemic
Castilleja linariifolia
Chrysopsis villosa
Cirsium rydbergii -- endemic
Comandra umbellata
Euphorbia brachycera
Habenaria zothecina -- endemic
Mimulus eastwoodiae -- endemic
Oenothera longissima
Panicum acuminatum
Primula specuicola -- endemic

Upper Courthouse Wash – at boundary

Cercocarpus intricatus
Clematis ligusticifolia
Grindelia fastigata
Rhus aromatica

Granstaff Campground – Colorado River

Acroptilon repens -- exotic
Datura wrightii
Kochia scoparia -- exotic
Populus angustifolia x *P. fremontii* --
planted
Populus deltoides -- planted
Rhus trilobata
Salix exigua
Solanum spp. -- exotic
Sphaeralcea spp.

Goose Island Campground – Colorado
River

Celtis cv -- planted
Celtis reticulata
Elaeagnus angustifolia -- exotic
Mulberry cv.
Populus deltoides -- planted
Rhus trilobata
Salix exigua
Salix gooddingii – probably planted

Canyonlands National Park (CANY)

NPS Support Staff

Matt Van Scoyoc supported the survey at Canyonlands National Park (CANY). His assistance allowed us to efficiently find sites where bioindicator and sensitive plant species were located, directed us to watercourse and moist habitats and assured accurate identification of plants in the field. The field assessment at CANY was conducted on August 15-16, 2016.

Ozone Exposure and Precipitation

Ambient ozone data collected at CANY were used to calculate ozone exposure indices for the past 11 years including 2016 (Table 4). The ozone data show moderately high levels of exposure from 2006 through 2016. The W126-7mo exposure summation significantly exceeded the criterion of 5.9 ppm-hr each year, however there were no years in which the second index criterion of 6 hours over 100 ppb was satisfied. Consequently, the overall W126-7mo exposure index threshold was not attained in any year. The W126-3mo index exceeded the 5 to 9 ppm-hr threshold each of the past 11 years. The Sum06 index threshold of 8 to 12 ppm-hr was exceeded in 10 of the years, but not in 2016. Overall, the levels of ozone exposure have been decreasing over the past 3 years as is apparent in the W126 3-mo, Sum06 and N60 values.

The N-values indicate that exposure to concentrations greater than 60 ppb was between 414 and 875 hours between 2006 and 2013, but significantly lower the last 3 years with 186 hours in 2016. Most years had 3 or fewer hours greater than 80 ppb, with a maximum of 8 hours in 2012, and no hours exceeded 100 ppb in the 11 years of assessment.

Precipitation at CANY ranged from 139 mm to 296 mm over the past 11 years with an average of 217 mm. In 2016 there was 247 mm of precipitation.

The ozone exposure indices and N-values for 2016 indicate it was a year of low ozone exposure at CANY. The W126 3-mo value of 8.7 ppm-hr, Sum06 value of 6.4 ppm-hr and N60 value of 186 hours were the lowest in the 11 years of data compiled. The 247 mm of precipitation was slightly above the 11-year average.

Ozone Bioindicator and Sensitive Plant Species

Comparison of the floral list for CANY with the list of plant species known to be bioindicators for or sensitive to ozone indicated there were potentially 2 bioindicator and 5 sensitive species to be found in the park (Table 5). These species were emphasized in the search for foliar ozone injury. Due to the lack of research information about the ozone sensitivity of the vast majority of plants found on the Colorado Plateau and at CANY, it was decided to also examine the foliage of other species opportunistically encountered in the field.

Field Survey Locations, Plant Species Examined and Results

Plants were assessed for foliar ozone injury at 6 sites at CANY with between 1 and 9 species examined at each site (Table 6). The only ozone bioindicator species found and examined was *Rhus aromatica* (fragrant sumac). Some of the locations visited were dry streambeds or where some subsurface moisture may have been available to the plants; no sites had standing or flowing water. Plants growing in moist rock alcove communities were also examined. These sites probably had the most optimum levels of available soil moisture.

No foliar ozone injury was observed at CANY. *Rhus aromatica* was examined on 3 sites and found to be uninjured. Collectively, the low level of ozone exposure and moderate precipitation at CANY in 2016 did not favor the production of foliar injury on even bioindicator species.

Conclusions

The levels of ambient ozone at CANY have historically exceeded injury thresholds by significant margins. Those levels were high enough to produce foliar injury if plants were actively exchanging gases with the atmosphere. Thus, soil moisture is a critical factor influencing the production of foliar ozone injury at CANY. Records indicate that levels of precipitation in some past years with high levels of ozone were up to 20% greater than that received in 2016 and 36% greater than average. The ozone and precipitation histories suggest that conditions favorable for the production of foliar injury on highly sensitive plants can be present at CANY. However, the low level of ozone exposure and more average precipitation in 2016 did not favor the development of foliar injury.

Given the historical exposure and precipitation data and the nature of some of the sites visited at CANY, it seems reasonable to consider conducting assessments for foliar injury in selected years in the future. When the levels of ozone exposure and precipitation in a particular year suggest conditions are favorable for the development of foliar injury, plant communities in moist rock alcoves should be examined. The alcove community examined at Neck Springs contained a diversity of species, including *Rhus aromatica*, growing under comparatively moist soil conditions. Depending on the configuration and aspect of an alcove plant community it may be somewhat shaded and not well ventilated. Both of these factors can reduce the response of plants to ozone, but the availability of soil moisture on these sites is a critical factor that can significantly facilitate the production of foliar injury.

Table 4. Ozone exposure indices for Canyonlands National Park for 2006 through 2016. Precipitation data are also provided for each year. Units: W126-7mo, W126-3mo and Sum06 are ppm-hr; N-values are number of hours; precipitation in mm for the Oct – Sept water year. Exposure indices in bold exceed the injury threshold.

Year	W126-7 mo*	W126-3 mo*	3 mo period	Sum 06*	N60	N80	N100	Precip
2006	28.3	17.6	May - Jul	27.6	791	0	0	163
2007	29.2	16.5	May - Jul	23.4	875	1	0	217
2008	27.5	16.6	Apr - Jun	24.4	747	2	0	202
2009	22.4	11.7	Mar - May	10.8	445	0	0	139
2010	20.5	12.8	Apr - Jun	15.5	499	3	0	215
2011	23.1	13.2	May - Jul	15.3	571	1	0	271
2012	27.8	15.7	May - Jul	21.9	832	8	0	185
2013	21.4	12.3	Apr. - Jun	15.3	414	0	0	179
2014	17.1	10.3	Apr - Jun	8.0	242	0	0	268
2015	15.9	10.3	Apr - Jun	9.5	277	0	0	296
2016	14.8	8.7	May-Jul	6.4	186	0	0	247

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

Table 5. Ozone bioindicator and sensitive species in Canyonlands National Park. Bioindicator species are in bold type.

<u>Scientific Name</u>	<u>Common Name</u>	<u>Bioindicator</u>
<i>Apocynum cannabinum</i>	Indian hemp	no
<i>Asclepias incarnata</i>	swamp milkweed	no
<i>Mentzelia albicaulis</i>	white-stemmed evening-star	yes
<i>Poa pratensis</i>	Kentucky bluegrass	no
<i>Rhus aromatica</i> var. <i>aromatica</i>	fragrant sumac	yes
<i>Salix exigua</i> var. <i>exigua</i>	coyote willow	no
<i>Salix gooddingii</i>	Goodding's willow	no

Table 6. Locations visited and plants examined in field survey to search for foliar ozone injury at Canyonlands National Park August 15-16, 2016.

NEEDLES DISTRICT

Little Spring Canyon

Apocynum cannabinum
Cerocarpus intricatus
Fraxinus anomala
Populus fremontii
Rhus aromatica
Solidago missouriensis
Symphoricarpos longiflorus

Squaw Flats

Helianthus petiularis

Salt Creek

Apocynum cannabinum
Atriplex canescens
Clematis sp.
Helianthus annua
Melilotus officinalis
Oenothera longissima
Populus fremontii
Salix exigua
Xanthium strumarium

ISLAND IN THE SKY DISTRICT

Neck Springs Trail

Cerocarpus intricatus
Comandra umbellata
Cornus sericea
Fraxinus anomala
Mahonia fremontii
Quercus gambelii
Rhus aromatica
Ribes aureum
Solidago missouriensis

Neck Springs

Amelanchier utahensis
Cerocarpus intricatus
Cornus sericea
Rhus aromatica
Rosa woodsii
Quercus gambelii

Potash Road

Datura wrightii
Forestiera pubescens
Grindelia fastigiata
Populus fremontii
Salix exigua
Xanthium strumarium

Colorado National Monument (COLM)

NPS Support Staff

Matthew Marques and Molly Murphy assisted in planning for and conducting the field survey at COLM. Molly Murphy's support in the field allowed us to efficiently find sites where bioindicator and sensitive plant species were located, and also directed us to watercourse and other habitats where additional plant species could be examined. She and her summer interns Jessica McCulloch and Stacey Birlson had clearly given considerable thought to where we should go to find plants of interest and her field botany expertise was invaluable. The assessment at COLM was conducted on August 8, 2016.

Ozone Exposure and Precipitation

Ambient ozone data collected at COLM were used to calculate ozone exposure indices for the past 11 years including 2016 (Table 7). The ozone data show generally decreasing levels of exposure over this period. The W126-7mo exposure summation exceeded the criterion of 5.9 ppm-hr each of the 7 years calculated, however there were no years in which the second index criterion of 6 hours over 100 ppb was satisfied. Consequently, the overall W126-7mo exposure index threshold was not attained in any year. The W126-3mo index exceeded the 5 – 9 ppm-hr threshold 9 of the past 11 years, but not in 2016. The Sum06 index threshold of 8-12 ppm-hr was generally exceeded in the early years, but has been exceeded only 3 times during the past 8 years and not in 2016.

The N-values indicate that the number of hours of exposure to concentrations greater than 60 ppb at COLM is decreasing. After a high of 871 hours greater than 60 ppb in 2006, there were less than 200 hours in each of the past 4 years, and only 21 hours in 2016. A total of 8 hours of exposure to concentrations greater than 80 ppb occurred between 2006 and 2016, and no hours exceeded 100 ppb in that time period.

Precipitation at COLM ranged from 236 mm to 552 mm over the past 7 years with an average of 416 mm. In 2016 there was 353 mm of precipitation.

The ozone indices and N-values indicate 2016 was a year of low ozone exposure at COLM. The W126 3-mo value of 3.9 ppm-hr and the Sum06 value of 1.2 ppm-hr were below their injury thresholds and were the lowest and second lowest values, respectively, for each index. The N60 value of 21 hours was the lowest in all the years of data compiled. The 214 mm of precipitation in 2016 was less than average, and third lowest in the 7 years of data available.

Ozone Bioindicator and Sensitive Plant Species

Comparison of the floral list for COLM with the list of plant species known to be bioindicators for or sensitive to ozone indicated there were potentially 5 bioindicator and 6 sensitive species to be found in the park (Table 8). These species were emphasized in the search for foliar ozone injury. Due to the lack of research information about the

ozone sensitivity of the vast majority of plants found on the Colorado Plateau and at COLM, it was decided to also examine the foliage of other species opportunistically encountered in the field.

Field Survey Locations, Plant Species Examined and Results

Plants were assessed for foliar ozone injury at 8 sites at COLM with between 1 and 7 species examined at each site (Table 9). The only ozone bioindicator species found and examined at COLM was *Rhus aromatica* (fragrant sumac). There are no continuously flowing watercourses at COLM. Consequently the locations visited were dry washes, washes with standing water or slightly moist habitats.

No foliar ozone injury was observed at COLM. *Rhus aromatica* was assessed on 2 sites and found to be uninjured. Collectively, the levels of ozone exposure and precipitation at COLM in 2016 were both low and did not produce foliar injury on even bioindicator species.

Conclusions

While the levels of ambient ozone at COLM have historically exceeded the thresholds for foliar injury, they have been decreasing over the past 8 years. Precipitation over the past 7 years has been moderate. With no flowing water at COLM and few sites with standing water, it is unclear how actively plants may be exchanging gases with the atmosphere over the summer. The decreasing levels of ambient ozone and limited soil moisture availability on most sites are critical factors reducing the probability of foliar ozone injury being produced on sensitive species at COLM, and were likely important constraints in 2016.

The most favorable habitat visited for the possible production of foliar ozone injury was Echo Canyon where there were scattered pools of standing water and a diversity of plant species. Unfortunately, an afternoon thunderstorm and accompanying flash flood in the canyon precluded an extended search for foliar injury at the site. While the moisture and plant community variables at Echo Canyon are favorable, the effects of the canyon's narrow topography on air movement and ventilation are unknown, but likely reduce the levels of ozone exposure. Since there are no continuously flowing watercourses at COLM, Echo Canyon and similar sites may be the most favorable ones in which to search for foliar ozone injury.

Willows dominated several of the assessment sites visited at COLM. While most willows are not highly sensitive to ozone, the moist soil conditions at these sites may foster growth of other less dominant species some of which may be more sensitive to the pollutant. It may be worthwhile to dedicate some time looking closely at willow sites to determine whether there may be other plant species more sensitive to ozone found there.

Table 7. Ozone exposure indices for Colorado National Monument for 2006 through 2016. Precipitation data are also provided for each year. Units: W126-7mo, W126-3mo and Sum06 are ppm-hr; N-values are number of hours; precipitation in mm for the Oct – Sept water year. Exposure indices in bold exceed the injury threshold.

Year	W126-7 mo*	W126-3 mo*	3 mo period	Sum 06*	N60	N80	N100	Precip
2006	NA	22.9	May – Jul	38.3	871	4	0	NA
2007	NA	11.1	Jun – Aug	13.3	253	0	0	NA
2008	NA	14.6	May – Jul	19.3	559	1	0	NA
2009	NA	3.6	Jul – Sep	1.0	29	0	0	NA
2010	15.8	9.8	Apr – Jun	9.9	213	0	0	250
2011	13.6	8.2	Apr - Jun	5.8	154	1	0	532
2012	17.1	9.8	Apr – Jun	9.8	248	2	0	236
2013	14.4	9.4	May – Jul	9.3	183	0	0	376
2014	11.1	6.9	Apr – Jun	4.4	80	0	0	552
2015	11.4	7.4	Apr – Jun	5.8	111	0	0	510
2016	6.4	3.9	May-Jul	1.2	21	0	0	353

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

Table 8. Ozone bioindicator and sensitive species at Colorado National Monument. Bioindicator species are in bold type.

<u>Scientific Name</u>	<u>Common Name</u>	<u>Bioindicator</u>
<i>Achillea millefolium</i>	common yarrow	no
<i>Apocynum androsaemifolium</i>	spreading dogbane	yes
<i>Apocynum cannabinum</i>	Indian hemp	no
<i>Campsis radicans</i>	common trumpet creeper	yes
<i>Mentzelia albicaulis</i>	white-stemmed evening-star	yes
<i>Poa pratensis</i>	Kentucky bluegrass	no
<i>Populus tremuloides</i>	quaking aspen	yes
<i>Rhus aromatica</i> var. <i>aromatica</i>	fragrant sumac	yes
<i>Robinia pseudoacacia</i>	black locust	no
<i>Salix exigua</i>	desert willow	no
<i>Salix gooddingii</i>	Goodding's willow	no

Table 9. Locations visited and plant species assessed in field survey for foliar ozone injury at Colorado National Monument August 8, 2016. Bioindicator species are in bold type.

16.5 Road Wash

Salix spp.

Rim Rock Road

Asclepias speciosa

Rim Rock Road – Upper Ute Canyon , Mile Marker 12.3

Amelanchier utahensis

Asclepias speciosa

Cercocarpus montanus

Old Gordon's Trail

Cercocarpus montanus

Fraxinus anomala

Echo Canyon

Amelanchier utahensis

Aster spp.

Fraxinus anomala

Grindelia fastigiata

Hedysarum boreale

Pinus edulis

Rhus aromatica

Upper Wash 11

Rhus aromatica

Upper Ute Wash

Glycyrrhiza lepidota

Salix spp.

Upper Wash 7

Salix spp.

Dinosaur National Monument (DINO)

NPS Staff Support

Members of the NPS staff at Dinosaur National Monument (DINO) were unable to provide field support due to prior commitments. However, staff member Tamara Naumann did provide information regarding locations in the park to examine. Mike Bell of the NPS Air Resources Division (ARD) in Denver performed an assessment of the possible sites to visit and was in the field to identify the plant species and assist with the examination of foliage for ozone injury. The field assessment at DINO was conducted on August 9, 2016.

Ozone Exposure and Precipitation

Ambient ozone data collected at DINO were used to calculate ozone exposure indices for the past 11 years including 2016 (Table 10). The ozone data show moderately variable levels of annual exposure over that period. The W126-7mo exposure summation significantly exceeded the criterion of 5.9 ppm-hr each year, but there were no years in which the index criterion of 6 hours over 100 ppb was satisfied. Consequently, the W126-7mo exposure index threshold was not satisfied at DINO in any year. The W126-3mo index exceeded the 5 to 9 ppm-hr injury threshold each year. The Sum06 index threshold of 8 to 12 ppm-hr was exceeded in 7 of the first 8 years, but in only 1 of the past 3 years and not in 2016.

The N-values indicate the number of hours of exposure to concentrations greater than 60 ppb ranged between 140 and 895 hours over the past 11 years. During the same period, concentrations did not exceed 80 ppb in 8 years with from 6 to 22 hours in the remaining 3 years, and there were no hours exceeding 100 ppb in the 11 years. The highest year of ozone for all indices and N-values at DINO occurred in 2012.

Precipitation at DINO ranged from 69 mm to 332 mm over the past 11 years. The average level of precipitation for the period was 138 mm, and the high of 332 mm occurred in 2016.

The ozone exposure indices and N-values for 2016 indicate it was a year of low ozone exposure at DINO. The W126 3-mo value of 8.4 ppm-hr and Sum06 value of 5.9 ppm-hr were the second lowest for each index in the 11 years of data compiled. Considering their interactive effects, even though the high level of precipitation may have fostered gas exchange with the atmosphere by the plant, the low levels of ozone taken up did not induce foliar injury.

Ozone Bioindicator and Sensitive Plant Species

Comparison of the floral list for DINO with the list of plant species known to be bioindicators for or sensitive to ozone indicated there were potentially 5 bioindicator and 6 sensitive species to be found in the park (Table 11). These species were emphasized in

the search for foliar ozone injury. Due to the lack of research information about the ozone sensitivity of the vast majority of plants found on the Colorado Plateau and at DINO, it was decided to also examine the foliage of other species opportunistically encountered in the field.

Field Survey Locations, Plant Species Examined and Results

Plants were assessed for foliar ozone injury at 5 sites at DINO with between 3 and 7 species examined at each site (Table 12). The only ozone bioindicator species found and examined at DINO was *Rhus aromatica* (fragrant sumac). Several of the locations visited were streamside or near flowing water where soil water was likely not a significant constraint to gas exchange by the plants.

No foliar ozone injury was observed at DINO. *Rhus aromatica* was examined on 3 sites and found to be uninjured. As indicated previously, the levels of ozone exposure at DINO in 2016 were among the lowest in the 11 years of data and did not favor the production of foliar injury on even bioindicator species.

Conclusions

In most previous years, the levels of ambient ozone at DINO were high enough to produce foliar injury if the plants had been actively exchanging gases with the atmosphere. An inverse relationship between ambient ozone and precipitation was clearly evident at DINO in 2 of the 11 years of data. As described above, 2016 experienced very low levels of ozone and high precipitation, while 2012 experienced the opposite with high levels of ozone and low precipitation. Given that either low ozone or precipitation can serve to severely constrain the development of foliar injury, years in which ozone and precipitation are moderate may be more favorable for the development of foliar injury.

Precipitation may not be as important for sites at DINO that are located near a river or stream that can provide subsurface water and plants on these sites may be injured at lower levels of exposure. Since DINO has numerous sites along rivers and streams, it is recommended that park staff examine ozone bioindicator species at these locations when ozone exposure levels during the summer indicate levels of stress may be high enough to induce injury.

Table 10. Ozone exposure indices for Dinosaur National Monument for 2006 through 2016. Precipitation data are also provided for each year. Units: W126-7mo, W126-3mo and Sum06 are ppm-hr; N-values are number of hours; precipitation in mm for the Oct – Sept water year. Exposure indices in bold exceed the injury threshold.

Year	W126-7 mo*	W126-3 mo*	3 mo period	Sum 06*	N60	N80	N100	Precip
2006	20.6	13.2	May – Jul	18.5	421	0	0	98
2007	16.8	10.6	May – Jul	9.1	173	0	0	85
2008	22.2	10.4	May – Jul	16	455	0	0	86
2009	15.5	7.9	May – Jul	5.6	144	0	0	105
2010	21.9	13.3	May – Jul	17.7	406	6	0	108
2011	15.7	11.0	Jun – Aug	13.6	264	0	0	209
2012	32.3	17.8	Jun – Aug	25.8	895	22	0	89
2013	12.5	10.6	Mar – May	9.5	140	0	0	69
2014	15.9	9.1	May – Jul	7.7	157	0	0	132
2015	16.9	10.6	Apr – Jun	11.6	257	0	0	200
2016	13.6	8.4	Jun-Aug	5.9	153	12	0	332

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

Table 11. Ozone bioindicator and sensitive species in Dinosaur National Monument. Bioindicator species are in bold type.

<u>Scientific Name</u>	<u>Common Name</u>	<u>Bioindicator</u>
<i>Achillea millefolium</i>	common yarrow	no
<i>Amelanchier alnifolia</i>	Saskatoon serviceberry	no
<i>Apocynum cannabinum</i>	Indian hemp	no
<i>Asclepias incarnata</i>	swamp milkweed	no
<i>Mentzelia albicaulis</i>	white-stemmed evening-star	yes
<i>Oenothera elata</i> ssp. <i>Hookeri</i>	Hooker's evening primrose	yes
<i>Poa pratensis</i>	Kentucky bluegrass	no
<i>Populus tremuloides</i>	quaking aspen	yes
<i>Rhus aromatica</i> var. <i>aromatica</i>	fragrant sumac	yes
<i>Salix exigua</i> var. <i>exigua</i>	coyote willow	no
<i>Salix scouleriana</i>	Scouler's willow	yes

Table 12. Locations visited and plants examined in field survey to search for foliar ozone injury at Dinosaur National Monument August 9, 2016. Bioindicator species are in bold type.

Split Rock Canyon – streamside south of boat ramp

Chrysothamnus spp.
Glycyrrhiza lepidota
Populus fremontii
Rhus aromatica
Salix exigua

Split Rock Canyon – streamside north of boat ramp

Apocynum cannabinum
Populus fremontii
Salix exigua

Green River Campground – campfire circle

Chrysothamnus spp.
Glycyrrhiza lepidota
Populus fremontii
Rhus aromatica
Salix exigua

Cub Creek

Apocynum cannabinum
Asclepias speciosa
Chrysothamnus spp.
Glycyrrhiza lepidota
Populus fremontii
Rhus aromatica
Salix exigua

Hog Canyon Trailhead – site of old homestead with introduced species

Acer glabrum var. *glabrum*
Apocynum cannabinum
Asclepias speciosa
Helianthus speciosa
Mentha arvensis var. *glabra*
Populus alba
Salix exigua

Mesa Verde National Park (MEVE)

NPS Staff Support

Tova Spector supported the survey at Mesa Verde National Park (MEVE). Her assistance in the field allowed us to efficiently find bioindicator and sensitive plant species and travel to watercourse and moist habitats where additional plant species could be examined. Tova provided skilled expertise as a field botanist and was particularly helpful in directing us to a site where the ozone bioindicator species *Populus tremuloides* could be found. The field assessment at MEVE was conducted on August 17-18, 2016.

Ozone Exposure and Precipitation

Ambient ozone data collected at MEVE were used to calculate ozone exposure indices for the past 11 years including 2016 (Table 13). The data show generally consistent but somewhat decreasing levels of exposure over that period. The W126-7mo exposure summation significantly exceeded the criterion of 5.9 ppm-hr each year, however there were no years in which the second index criterion of 6 hours over 100 ppb was satisfied. Consequently, the overall W126-7mo exposure index threshold was not attained in any year. The W126-3mo index exceeded the 5 to 9 ppm-hr threshold each of the past 11 years. The 8 to 12 ppm-hr Sum06 index threshold was also exceeded in each year of the assessment.

The N-values indicate that the number of hours of exposure to concentrations greater than 60 ppb at MEVE was significant with 6 years having over 500 hours and no year with fewer than 252 hours. The N60 values were the highest in 2006 and have been considerably lower the last 3 years. Hours of exposure to concentrations greater than 80 ppb were low or zero and no hours of exposure exceeded 100 ppb. The ozone exposure indices and N-values indicate that ozone exposure at MEVE in 2016 was below average.

Precipitation at MEVE ranged from 223 mm to 407 mm over the past 11 years. The average for the period was 352 mm, and the 402 mm in 2016 tied for the second highest.

Ozone Bioindicator and Sensitive Plant Species

Comparison of the floral list for MEVE with the list of plant species known to be bioindicators for or sensitive to ozone indicated there were potentially 7 bioindicator and 7 sensitive species to be found in the park (Table 14). These species were emphasized in the search for foliar ozone injury. Due to the lack of research information about the ozone sensitivity of the vast majority of plants found on the Colorado Plateau and at MEVE, it was decided to also examine the foliage of other species opportunistically encountered in the field.

Field Survey Locations, Plant Species Examined and Results

Plants were assessed for foliar ozone injury on 9 sites at MEVE with between 1 and 9 species examined at each site (Table 15). The ozone bioindicator species *Rhus aromatica* (fragrant sumac), *Artemisia ludoviciana* (white sagebrush), *Apocynum androsaemifolium* (spreading dogbane), and *Populus tremuloides* (quaking aspen) were assessed.

No foliar ozone injury was observed at MEVE on the 4 bioindicator species observed over 6 sites. While precipitation was high in 2016, ozone levels were below average and uptake by plants was apparently not great enough to produce foliar injury on bioindicator species.

Conclusions

The historic levels of ambient ozone at MEVE were high enough to produce foliar injury if plants had been actively exchanging gases with the atmosphere. There seems to be a loose inverse relationship between ozone levels and precipitation. Precipitation was highest in years with the lowest levels of ozone and more moderate in years with higher levels of exposure. Although the temporal pattern of the precipitation is not known, it is likely that in years with moderate to low precipitation soil moisture may be lowest during the summer months when ozone is highest.

The Prater Tunnel site is a road-cut sidehill well populated with *Apocynum androsaemifolium*, possibly planted. The site is well exposed and the soil stony and seemingly well drained. The site is readily accessible and should be considered a location to be visited by NPS staff annually to look for foliar ozone injury.

Populus tremuloides was found on only one site in MEVE, Prater Side Canyon. No ozone injury was found on the trees, but due to the abundance of trees and their classification as a bioindicator species, this site should be considered for annual assessment. While access to the site in the upper part of the canyon is somewhat challenging, foliage should be collected with a pole pruner from mid-canopy branches that are exposed to the atmosphere and sun.

Although the North Mancos River site is not easily accessible, it should be considered for injury assessment. The site is of value since it has populations of both *Rhus aromatica* (fragrant sumac) and *Asclepias speciosa* (milkweed). Both of these species have the potential to be injured by ozone, and was the only site visited that had a population of milkweed.

Table 13. Ozone exposure indices for Mesa Verde National Park for 2006 through 2016. Precipitation data are also provided for each year. Units: W126-7mo, W126-3mo and Sum06 are ppm-hr; N-values are number of hours; precipitation in mm. Exposure indices in bold exceed the injury threshold that year.

Year	W126-7 mo*	W126-3 mo*	3 mo period	Sum 06*	N60	N80	N100	Precip
2006	35.6	23.0	May – Jul	40.3	1111	12	0	223
2007	32.0	17.1	May – Jul	25.8	822	0	0	373
2008	18.8	12.9	Apr – Jun	17.3	447	0	0	402
2009	26.9	14.6	Jun – Aug	19.1	643	1	0	330
2010	19.8	11.5	Apr – Jun	13.6	384	3	0	376
2011	25.7	15.4	Jun – Aug	21.5	655	4	0	367
2012	26.2	14.1	May – Jul	18.6	652	0	0	250
2013	25.3	16.0	May – Jul	22.4	572	0	0	347
2014	19.2	10.9	May – Jul	10.0	252	0	0	407
2015	17.4	11.0	Apr – Jun	9.7	257	0	0	398
2016	19.6	12.3	May –Jul	13.5	343	0	0	402

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

Table 14. Ozone bioindicator and sensitive species at Mesa Verde National Park. Bioindicator species are in bold type.

<u>Scientific Name</u>	<u>Common Name</u>	<u>Bioindicator</u>
<i>Achillea millefolium</i>	common yarrow	no
<i>Amelanchier alnifolia</i>	saskatoon serviceberry	no
<i>Apocynum androsaemifolium</i>	spreading dogbane	yes
<i>Apocynum cannabinum</i>	Indian hemp	no
<i>Artemisia ludoviciana</i>	white sagebrush	yes
<i>Mentzelia albicaulis</i>	white-stemmed evening-star	yes
<i>Oenothera elata ssp. hookeri</i>	Hooker's evening primrose	yes
<i>Pinus ponderosa</i>	ponderosa pine	yes
<i>Poa pratensis</i>	Kentucky bluegrass	no
<i>Populus tremuloides</i>	quaking aspen	yes
<i>Prunus americana</i>	American plum	no
<i>Prunus virginiana</i>	common chokecherry	no
<i>Rhus aromatica var. aromatic</i>	fragrant sumac	yes
<i>Salix exigua</i>	desert willow	no

Table 15. Locations visited and plants examined in field survey to search for foliar ozone injury at Mesa Verde National Park August 17-18, 2016.

Morefield / Sand Shed

Achillea millefolium
Artemisia ludoviciana
Eriogonum racemosum
Erigeron speciosus
Lepidium crenatum
Lupinus argenteus
Ribes leptanthum
Rosa woodsii
Symphoricarpos oreophilus

Morefield / Cell

Chenopodium simplex
Lepidium crenatum
Salix exigua

Prater Tunnel / Exposed Roadside

Apocynum androsaemifolium

Prater Tunnel / Woodside

Acer negundo
Castilleja linarifolia
Prunus virginiana
Rhus aromatica

North Mancos River Canyon

Asclepias speciosa
Glycyrrhiza lepidota
Populus angustifolia
Rhus aromatica
Shepherdia argentea

Visitor Research Center Field

Asclepias subverticillata
Helianthus annua
Peraphyllum ramosissimum

Prater Side Canyon

Amelanchier utahensis
Brickellia californica
Maianthemum racemosum
Maianthemum stellatum
Populus tremuloides

Big Hill Hairpin

Mentzelia lacinata

Spruce Tree House

Amelanchier alnifolia
Brickellia californica
Cercocarpus montanus
Prunus virginiana
Rhus aromatica
Salix amygdaloides

OBSERVATIONS AND RECOMMENDATIONS

The levels of ozone exposure in the parks on the Colorado Plateau were historically high enough to potentially produce foliar injury on bioindicator plant species. In many years the injury thresholds for the W126-3 mo and Sum06 indices were exceeded by significant margins and the N60 values were quite high. However in some parks the levels of exposure have declined over the past 3 to 5 years. Parks in which this decrease is most obvious are ARCH/CANY and COLM with a less clear decline in MEVE. Exposure levels during this period at DINO are variable with some unusually high N-values in 2011, 2012 and 2013. It would be useful to conduct an assessment of the possible relationships between fracking activity upwind and the reductions in ozone exposures in these parks. Fracking activity could be measured in overall number of working wells, number of new wells drilled or amount of oil or gas produced.

Unfortunately, with respect to the survey for foliar injury, the levels of ozone in 2016 were low in most of the parks (ARCH, CANY, COLM, DINO). This effectively prevented the development of foliar injury on bioindicator species in spite of moderate to high levels of precipitation in some parks.

Historically, levels of precipitation and soil moisture appear to have generally been low enough to constrain the uptake of ozone in many years. This constraint serves as a significant limitation to the development of foliar ozone injury.

In some years the levels of ozone and precipitation were inversely related. This relationship is most evident at DINO in 2012 where ozone exposure indices were high and precipitation low and in 2016 where the indices were low and precipitation high. This inverse relationship between ozone and precipitation is not unexpected since the conditions that foster the photochemical production of ozone, high temperatures and intense sunlight, are those associated with reduced cloud cover and thus reduced precipitation. In contrast, the opposite temperature and solar radiation conditions lead to lower levels of ozone generation and are associated with precipitation.

Given the above relationship between the level of ozone and precipitation, the greatest risk for the development of foliar ozone injury may exist in those years when ozone levels are more moderate, but still above the thresholds for injury, and the level of precipitation is higher and more evenly distributed over time so that plants have a greater capacity to exchange gases during the growing season than they would in years with higher levels of ozone but more limited precipitation.

Most parks have areas where flowing water, pooled water or moist areas are found. Some of these areas contain plant species that are either bioindicators or sensitive to ozone. These areas are ones where parks should consider conducting foliar injury assessments in years when ambient levels of ozone are above the thresholds for injury.

It is important to understand that even though a plant does not develop foliar injury, it does not mean the plant has not been affected by the exposure to elevated levels

of ozone. Ozone does not kill plants, but rather debilitates them by impacting their carbon budget. Ozone taken up by a plant readily reduces its rate of photosynthesis and carbon fixation. Some of the fixed carbon is used to repair damage done by the exposure, and over time the reduced rate of fixation and increased use for repair results in less net carbon available for growth, reproduction, and overwintering (Leisner and Ainsworth 2012). The long-term alteration of the plant's carbon budget can reduce growth, seed production, and seed viability and make the plant more susceptible to impacts from insects and disease. These effects are subtle and long-term, and can occur without any visible foliar injury. The effects cannot be readily assessed in the field without intensive studies assessing rates of photosynthesis and respiration, growth, and reproduction.

During the 2016 field assessments, the NPS staff assisting at each park was coached in how to identify foliar ozone injury. Unfortunately since no injury was found, they were unable to actually see how to conduct a diagnosis and what the injury looked like on the plant. They did however see photographs of various types of foliar injury and I discussed the process of diagnosis with them. A valuable reference for diagnosing foliar ozone injury is the handbook I wrote for the NPS, Handbook for Assessment of Foliar Ozone Injury on Vegetation in the National Parks, Revised 2nd Edition (Kohut 2007). In addition, I will forward photographs of foliar injury and related material that provides additional information on diagnosing foliar injury to each staff member who assisted me. With this material, I believe the NPS staff will be capable of going to selected field sites in years where ozone exposures and levels of precipitation warrant conducting a first-effort in identifying foliar injury. If they photograph what they find and send them to me with a written description of the markings and how they are distributed on the plant, I will be willing and able to perform a second-level analysis of what they found. If the park considers it appropriate, collecting and forwarding a sample of pressed leaves would also be useful.

It will take some effort to determine which years have had ozone exposures high enough to warrant conducting a field assessment. The indices of exposure in the assessment are both complex to calculate and largely retrospective in nature and will not be available to guide making a real-time decision. The most effective way to assess the level of exposure will be to track N-values from April to August and compare them to those of previous years. If the rate at which N60 hours are accumulating or if N80 or N100 hours begin to appear, the year may be one in which the level of ozone exposure is of concern. If the exposure is accompanied by rates and levels of precipitation that are average or greater in the first part of the water year, conditions for plants to respond to the ozone exposures may be favorable and indicate a field assessment should be conducted. Since at most parks the number of sites to visit is limited, a meaningful assessment of injury can be completed in one day in August thus making the effort a feasible exercise.

It is useful to understand how the ozone exposure environment at the parks assessed on the Colorado Plateau compares with those in other national parks. Table 16 provides ozone and precipitation information for Acadia National Park (ACAD), Rocky Mountain National Park (ROMO), Sequoia-Kings Canyon National Park (SEKI) and Yellowstone

National Park (YELL). The ozone environments among these parks are significantly different from each other and also differ from those in the parks visited in this assessment.

Levels of ozone exposure at ACAD were relatively low and the injury thresholds not surpassed since 2007. However, surveys for foliar ozone injury at ACAD in the 1990's regularly found injury on *Apocynum androsaemifolium* (spreading dogbane) and *Aster macrophyllus* (big-leaf aster) (Eckert et al. 1999). Air quality monitoring at ROMO and SEKI showed significant levels of ozone each year. At ROMO the W126-7 mo index exceeded the cumulative threshold each year, but the N100 criterion is not satisfied, while the W126-3 mo and Sum06 indices were exceeded annually. Field surveys for foliar ozone injury were conducted at ROMO from 2006 through 2010 with injury found on *Rudbeckia laciniata* var *ampla* (cutleaf coneflower) each year (Kohut 2012). Ozone exposure levels at SEKI were greater for all indices than at ROMO. The W126-7 mo index at SEKI was satisfied most years since there were usually more than 6 hours of over 100 ppb exposure at the park. Historically, injury has been found on conifer species at SEKI (Carroll et al. 2003). The ozone exposure environment at YELL indicated the W126-3 mo and Sum06 thresholds were frequently surpassed. The trends in the magnitudes of the exposure indices and N-values at YELL suggest the levels of ozone stress may be declining. No surveys for foliar ozone injury have been conducted at YELL.

Comparing the ozone environments at the Colorado Plateau parks with the other four parks shows that the Plateau parks are more similar to those at YELL and ROMO than the more stressed SEKI or less stressed ACAD. Of course, the most notable differences between the parks on the Colorado Plateau and the others is their levels of precipitation and the roles these differences play in regulating the responses of the parks' vegetation to the ambient levels of ozone.

The lack of sound information about the ozone-sensitivity of plants on the Colorado Plateau, knowing whether they are bioindicators, sensitive or resistant species, is a significant constraint to effectively assessing the effects of ozone on plants in the parks. Eighty-one species of plants were examined during the survey only 5 of which were recognized as bioindicators for ozone. Extrapolation of research findings of plant sensitivity to ozone from other geographic regions where experimental plant growth conditions and ozone exposure treatments did not approximate those of the Colorado Plateau may currently be a necessity, but is risky at best. Given that ozone exposure levels in the parks often significantly exceed the thresholds for foliar injury and that specific habitats and some annual precipitation levels can favor pollutant uptake, it is essential to better understand which species on the Colorado Plateau are bioindicators for or sensitive to ozone. To obtain this information, it will be necessary to conduct controlled ozone exposures in an environment replicating desert temperature, soil and moisture conditions and using plant material obtained from the Colorado Plateau. The US Forest Service operates facilities at which this research can be conducted. If the National Park Service considers it is important to understand the threat ambient ozone poses to native vegetation on the Colorado Plateau, an interagency research agreement

would provide invaluable information on plant sensitivity for future assessments of injury.

The historic levels of ozone at the parks have been high, seem to have decreased in some parks and, if related to the level of fracking upwind, can be expected to increase again in the future. Given the unusually low levels of ozone in 2016, it should not be assumed that the lack of injury observed in the survey is representative of what occurs in other years. Preparation for and execution of these surveys have provided a wealth of information about the potential for foliar injury to be produced, the environmental conditions under which it would occur and the specific locations in each park where it is most likely to be found. Overall, this assessment provides valuable guidance on what additional information on plant sensitivity to ozone would be useful and when and how NPS staff can proceed in the assessment of foliar injury on plants in the parks.

Table 16. Ozone exposure indices for Acadia, Rocky Mountain, Sequoia-Kings Canyon and Yellowstone National Parks 2006 through 2016. Precipitation data are also provided for each year. Units: W126-7mo, W126-3mo and Sum06 are ppm-hr; N-values are number of hours; precipitation in mm for the Oct – Sept water year. Exposure indices in bold exceed the injury threshold.

Acadia National Park (ACAD)

Year	W126-7 mo	W126-3 mo	3 mo period	Sum 06	N60	N80	N100	Precip
2006	8.4	6.0	May - Jul	7.0	196	4	0	1367
2007	10.9	5.9	Apr - Jun	5.9	254	50	5	1263
2008	6.4	4.3	May - Jul	4.2	102	3	0	1413
2009	5.0	4.7	Mar - May	3.0	91	13	0	1375
2010	6.5	3.6	Mar - May	2.7	134	16	0	1527
2011	4.9	2.7	Jun - Aug	2.7	95	1	0	1181
2012	3.9	2.6	Mar - May	1.4	62	0	0	1207
2013	6.7	4.5	Apr - Jun	4.3	162	9	0	1124
2014	4.1	2.2	Apr - Jun	2.1	53	0	0	1179
2015	4.9	3.8	Mar - May	3.0	102	4	0	1309
2016	3.8	2.3	May - Jul	1.7	60	5	0	901

Rocky Mountain National Park (ROMO)

Year	W126-7 mo	W126-3 mo	3 mo period	Sum 06	N60	N80	N100	Precip
2006	29.7	18.3	Jun - Aug	25.6	672	20	3	361
2007	33.2	19.9	Jun - Aug	27.5	778	32	0	376
2008	28.9	17.6	May - Jul	24.0	710	27	0	397
2009	20.7	11.4	Jun - Aug	12.7	361	5	0	436
2010	35.0	18.9	Apr - Jun	27.5	840	37	0	541
2011	40.5	23.5	June - Aug.	35.0	1252	44	0	429
2012	47.0	27.0	May - July	41.5	1436	72	0	389
2013	25.9	16.7	May - July	21.8	536	24	0	766
2014	21.1	11.8	Apr. - June	12.5	343	5	0	495
2015	18.9	11.0	Apr - Jun	13.7	285	5	0	402
2016	23.4	14.2	Apr - Jun	17.3	446	12	0	391

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

Sequoia-Kings Canyon National Park (SEKI)

Year	W126-7 mo	W126-3 mo	3 mo period	Sum 06	N60	N80	N100	Precip
2006	96.8	66	Jul – Sep	79.3	1737	650	92	351
2007	103.2	62.8	Jun – Aug	78.2	1964	595	58	389
2008	114.8	39.9	Apr – Jun	51.0	1768	603	123	420
2009	82.3	55.2	Jul – Sep	69.2	1824	495	41	129
2010	72.8	53.6	Jul – Sep	69.0	1556	417	28	789
2011	87.1	60.4	July - Sept.	74.3	1778	597	59	956
2012	90.5	56.9	July - Sept.	74.0	2035	561	31	533
2013	78.5	44.4	June - Aug.	61.3	1690	315	15	355
2014	78.0	41.0	July - Sept.	58.9	1828	288	5	127
2015	68.6	40.6	Jun – Aug	56.4	1563	272	5	362
2016	75.6	55.5	Jun – Aug	74.1	1829	376	10	587

Yellowstone National Park (YELL)

Year	W126-7 mo	W126-3 mo	3 mo period	Sum 06	N60	N80	N100	Precip
2006	22.3	12.5	Mar – May	15.7	512	7	0	429
2007	15.4	9.5	Apr – Jun	10.1	210	0	0	425
2008	13.9	8.3	Mar – May	8.2	227	1	0	689
2009	10.3	7.1	Mar – May	4.6	114	8	3	366
2010	18.3	11.1	Apr – Jun	14.8	356	0	0	470
2011	17.1	11.0	Apr. - June	12.8	329	0	0	613
2012	17.2	10.1	Apr. - June	11.8	301	0	0	522
2013	11.3	6.5	May – July	4.9	113	0	0	410
2014	10.2	6.5	Apr. - June	3.7	98	0	0	653
2015	10.5	5.4	Mar – May	2.3	94	0	0	369
2016	8.5	5.0	Apr – Jun	3.0	85	0	0	401

- Ozone foliar injury thresholds:
W126-7mo -- 5.9 ppm-hr and 6 hr greater than 100ppb
W126-3mo -- 5-9 ppm-hr
Sum06 -- 8-12 ppm-hr

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