Evaluation of Ozone Injury
on Vegetation within the
Okefenokee National Wildlife Refuge
Georgia and Florida

2004 Observations

Submitted to

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Air Quality Branch
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INTRODUCTION

Description of the Refuge (adapted from refuge brochures)

The Okefenokee National Wildlife Refuge is one of more than 500 refuges in the National Wildlife Refuge (NWR) System. This system is a network of United States' lands and waters managed specifically for wildlife and is administered by the Department of the Interior's U.S. Fish and Wildlife Service (FWS). The Okefenokee refuge, located in southeastern Georgia and northeastern Florida (Figure 1), comprises eight predominant habitat types, including swamp islands, prairies (freshwater marsh), shrub swamp, mixed cypress forests, blackgum forests, bay forests, pure cypress forests, and managed upland pine forests.

The refuge was established in 1937 in order to preserve the 438,000-acre Okefenokee Swamp, and presently encompasses approximately 396,000 acres. In 1974, to further ensure the protection of this unique ecosystem, the interior 353,981 acres of the refuge were designated a National Wilderness Area. The swamp remains one of the oldest and most well preserved freshwater areas in America, and extends 38 miles north to south and 25 miles east to west.

Okefenokee is a vast bog inside a huge, saucer-shaped depression that was once part of the ocean floor. The swamp now lies 103 to 128 feet above mean sea level. Peat deposits, up to 15 feet thick, cover much of the swamp floor. These deposits are so unstable in spots that one can cause trees and surrounding bushes to tremble when jumping on the surface. The slow-moving waters of the Okefenokee are tea-colored due to the tannic acid released from decaying vegetation. The principle outlet of the swamp, the Suwanee River, originates in the heart of the Okefenokee and drains southwest into the Gulf of Mexico. The swamp's southeastern drainage to the Atlantic Ocean is the St. Mary's River, which forms the boundary between Georgia and Florida.

The swamp contains numerous islands and lakes, along with vast areas of non-forested terrain. Prairies cover about 60,000 acres of the swamp. Once forested, these expanses of marsh were created during periods of severe drought when intense fires burned off vegetation and the top layers of peat. The prairies harbor a variety of wading birds including herons, egrets, ibises, cranes and bitterns.

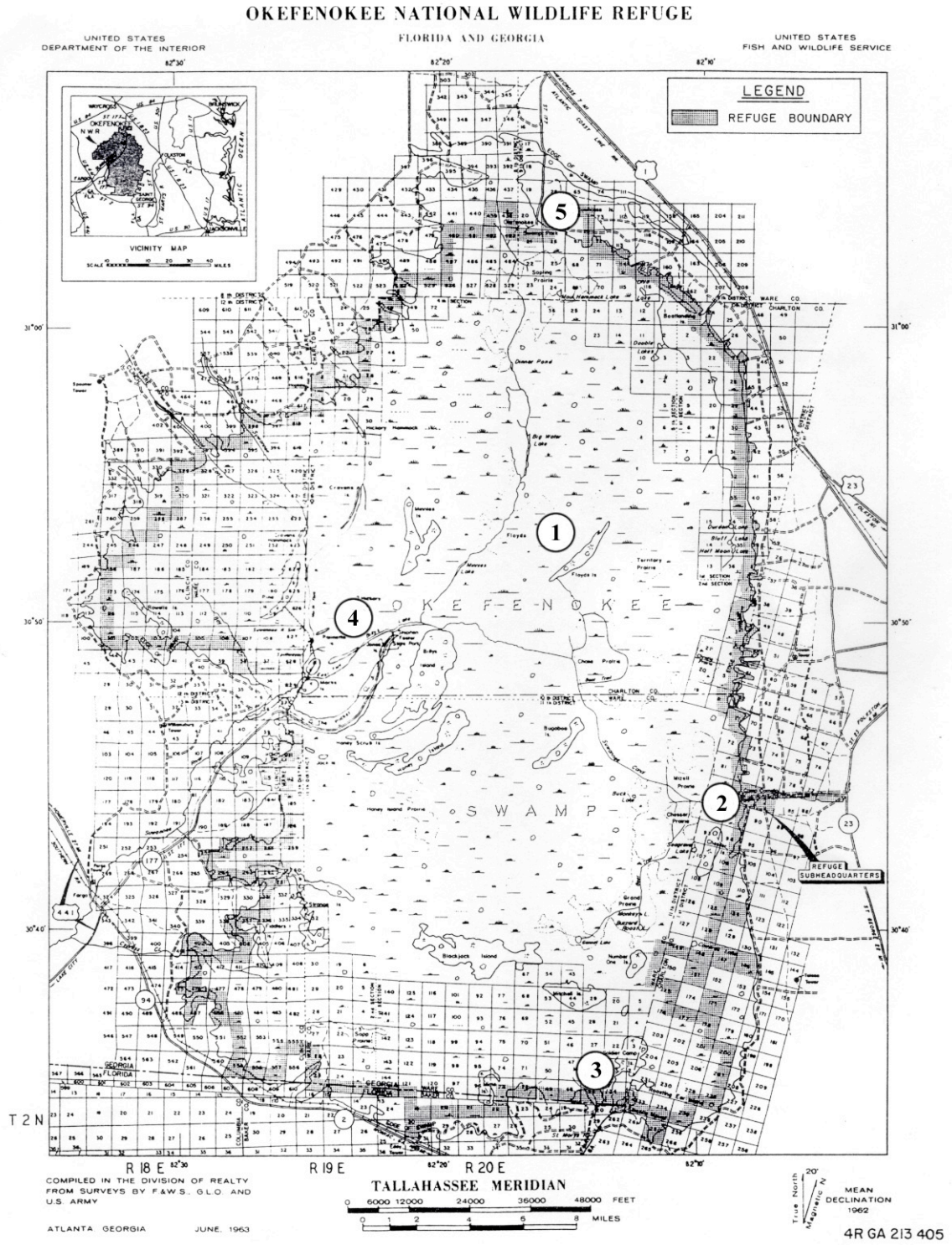

Figure 1. General map of the Okefenokee National Wildlife Refuge and location of survey plots.

History

Native Americans inhabited Okefenokee Swamp as early as 2500 B.C. Tribes of the Depford Culture, the Swift Creek Culture and the Weeden Island Culture occupied sites within the Okefenokee. The last tribe to seek sanctuary in the swamp, the Seminoles, conducted raids on settlers in surrounding areas. However, an armed militia led by General Charles R. Floyd ended the age of the Native American in 1850, by driving the Seminoles into Florida.

The Suwanee Canal Company purchased 238,120 acres of the Okefenokee Swamp from the State of Georgia in 1891. Their intent was to drain the land to facilitate logging and eventual crop cultivation. Captain Henry Jackson and his crews spent three years digging the Suwanee Canal 11.5 miles into the swamp. Economic recessions led to the company's bankruptcy and eventual sale to the Hebard Cypress Company in 1899. Logging operations, focusing on cypress, began in 1909 after a railroad was constructed into the west edge of the swamp. Over 431 million board feet of timber, much of it old-growth cypress, had been removed from the Okefenokee by 1927 when logging operations ceased.

Wildlife Management

Management activities within the refuge preserve the natural qualities of the NWR, provide habitat for a variety of wildlife, and provide recreational opportunities for visitors. The swamp's unique environmental qualities are preserved through protection, research and progressive management. Examples of endangered species benefited by these management efforts include the red-cockaded woodpecker, American alligator, wood stork, and American bald eagle.

Hunting, waterfowl banding, wildlife censuses, vegetative transects and water level recorders are used to monitor and manage wildlife populations and habitat conditions. Wildlife habitat is improved through the use of wildlife clearings, forest thinning and planting, and prescribed burning.

Recreation

Although primarily managed for wildlife, public use is an important aspect of the refuge. Visitor facilities are provided on a portion of the refuge, creating a place where wildlife, wild lands and people are brought together in harmony. Wildlife observation, photography, fishing, hunting during designated seasons, and hiking are permitted. Camping is allowed at designated areas, and canoeing and motor boating are permitted year-round. There are many miles of canoe trails through the Okefenokee Swamp, which may be traveled by campers holding permits.

The East entrance offers visitors access into the core of the Okefenokee via the man-made historic Suwanee Canal. The swamp's three most extensive open areas, the Chesser, Grand and Mizell prairies, branch off the Suwanee Canal. The small natural lakes and alligator holes dotting the prairies offer some of the area's finest freshwater sport fishing. Home of the Florida sandhill crane, the prairies are excellent sites for bird watching. Modern concession facilities offer guided boat tours; boat, motor, and canoe rentals; bicycles, snacks, and souvenirs, as well as camping and fishing supplies. A 4.5-mile wildlife observation drive, 4.5 miles of hiking trails, 4,000 foot boardwalk into the swamp, two observation towers, two photo blinds and a restored homestead are accessible to visitors.

The North entrance is via Okefenokee Swamp Park, a private, non-profit attraction operating under a leasing agreement with the U. S. Fish and Wildlife Service. The West entrance is via the 82-acre Stephen C. Foster State Park, a Georgia state park also operating under a leasing agreement with the U. S. Fish and Wildlife Service.

Air Quality

In 1978, Congress further acknowledged the uniqueness of the Okefenokee Wilderness Area by naming it a Class I air quality area and giving it special protection under the Clean Air Act. Congress gave the FWS, as the Federal Land Manager of the Okefenokee Wilderness Area, the responsibility to protect the air quality and air quality related values (AQRVs), including vegetation, wildlife, soils, water quality, visibility, and odor, as well as cultural and archeological resources, from anthropogenic air pollution.

Despite this protection, air pollution from upwind sources is impacting Okefenokee. The wilderness area is affected by pollution-caused regional haze. Rainfall carries pollutants such as mercury and other potentially harmful trace elements to the swamp. Florida has among the highest levels of mercury in the nation. Ozone likely affects the health of the vegetation, an important AQRV, in the Okefenokee. It is likely that ozone will remain the air pollutant of concern in terms of plant damage. Ozone currently has high potential to injure vegetation within the refuge, and may put certain ozone-sensitive plant species at risk.

Ozone concentrations have been monitored near the refuge since 1989. The ozone levels at these locations are relatively low, as compared to the ozone levels monitored in refuges located near urban areas in the East (i.e., Brigantine, NJ), but are still great enough to possibly cause injury on ozone-sensitive vegetation. However, there had not been a survey conducted to document the presence or absence of ozone injury within the refuge. Therefore, during August of 1997, D. D. Davis conducted the first U. S. Fish and Wildlife survey to evaluate ozone injury on vegetation within the NWR. This 1997 survey established an AQRV baseline to determine the status of the ozone-related health of the vegetation in the refuge. A second survey was conducted in 2004. Results of these two surveys give decision-makers background data to help make future decisions involving permitting the siting of new industries, whose emissions may influence ozone levels within the refuge.

The primary tool of the FWS in combating air pollution is participation in the review of Prevention of Significant Deterioration (PSD) air pollution permits. The FWS is responsible for reviewing PSD permit applications by facilities or industries wishing to expand or locate near Class I areas. These permit applications contain analyses of potential impacts to Class I areas, including impacts to AQRVs.

The FWS has begun a program to better understand air pollution causes and effects at Okefenokee. In addition, the FWS is working cooperatively with industry and the states of Georgia and Florida to reduce air pollutant emissions and protect the air quality and AQRVs of Okefenokee. If the Okefenokee is not protected, unique wildlife and scenic values will be threatened or even lost, as has happened in much of the eastern U.S. The Fish and Wildlife Service hopes to preserve and protect this special area of wilderness for future generations.

Diagnosis of Air Pollution Injury on Plants

Although many gaseous air pollutants are emitted into the atmosphere, only certain ones are phytotoxic and induce characteristic leaf symptoms that are useful during field surveys. The most important of these gaseous, phytotoxic air pollutants include ozone, sulfur dioxide, and ozone. Such pollutants, along with the normal constituents of the air, are taken into the plant leaf through the stomata during respiration. Once inside the leaf the pollutant, or its breakdown products, reacts with cellular components causing tissue injury or death. The resulting macroscopic symptoms, which are visible on the leaf surface, are classified as chronic or acute depending upon the severity of injury. Chronic symptoms imply tissue injury, whereas acute injury signifies tissue death. Chronic symptoms on foliage usually result a plant's exposure to low levels of pollution for an extended time, or occur when a plant is somewhat resistant to a pollutant. Visible ozone injury is usually considered to be chronic injury. Acute injury may be observed following a short-term, high concentration of pollution, or occurs when a plant is in a very sensitive condition.

Macroscopic leaf injury caused by air pollution often represents an intermediate step between initial physiological events and decreases in plant productivity. Decreases in plant productivity (Pye 1988) may result in ecological changes, such as reduced diversity (Rosenberg et al. 1979). Visible leaf symptoms induced by phytotoxic pollutants serve as important diagnostic tools that allow observers to identify specific air pollutants as causal agents of vegetation damage (Davis 1984; Skelly et al. 1987, Skelly 2000). This knowledge can be used in the air pollution emissions permitting process for siting new industries (i.e. Prevention of Significant Deterioration Program), assessment of the secondary air quality standards, assessing the presence of air pollution injury in Class I areas, and in litigation involving air pollution injury.

Although ozone was the air pollutant of concern in this survey, it should be recognized that phytotoxic levels of air primary pollutants such as sulfur dioxide and fluorides might occur near industrial sources. Likewise, trace elements including metals may be found in excessive levels in vegetation growing in areas downwind from industrial or urban sources (Davis et al. 1984, Davis et al. 2001). Toxic elements such as arsenic, mercury (Davis 2002), and lead may be especially important in areas being managed for wildlife. Although such compounds are of more interest in mammalian and avian toxicity as compared to phytotoxicity, vegetation may sorb such

contaminants and become part of the contaminated food chain. However, the presence of excessive elements such as metals, as well as organic biohazards such as dioxins and furans, is determined with laboratory analysis of foliage, not with field surveys that deal with macroscopic foliar injury.

Ozone

Ozone is the most important, phytotoxic air pollutant in the United States, and is the air pollutant most likely to have an easily recognizable impact on vegetation within a NWR. Background levels of ozone exist naturally in the lower atmosphere, possibly originating from vertical downdrafts of ozone from the stratosphere, lightning, or chemical reactions of naturally occurring precursors. However, in many areas, precursors leading to phytotoxic levels of ozone originate from upwind urban areas. In those areas, hydrocarbons and oxides of nitrogen are emitted into the atmosphere from various industrial sources and automobiles. These compounds undergo photochemical reactions in the presence of sunlight forming photochemical smog, of which ozone is a major component. Ozone, or its precursors may travel downwind for hundreds of miles during long-range transport, as influenced by wind direction and movement of weather fronts. Thus, ozone impinging on refuges may originate in areas many miles upwind from the refuge. In fact, concentrations of ozone are often greater in rural areas downwind from urban areas, as compared to within an upwind urban area, due to the presence of reactive pollutants in the urban air that scavenge the ozone.

There are certain bioindicator plants in the East that are very sensitive to ozone and exhibit characteristic symptoms when exposed to ozone (Anderson et al. 1989, Davis and Coppolino 1976, Davis and Skelly 1992, Davis et al. 1981, Davis and Wilhour 1976, and Jensen and Dochinger 1989). The principal investigator in this survey routinely uses the following broad-leaved bioindicator species for evaluating ozone injury: black cherry (*Prunus serotina*), common elder (*Sambucus canadensis*), common milkweed (*Asclepias syriaca*), grape (*Vitis* spp), white ash (*Fraxinus americana*), and yellow-poplar (*Liriodendron tulipifera*). The investigator also uses, but less commonly, Virginia creeper (*Parthenocissus quinquefolia*) and *Viburnum* spp.

Ozone-induced symptoms on broadleaved bioindicators usually appear as small 1-2 mm diameter "stipples" of pigmented, black or reddish-purple tissue, restricted by the veinlets, on the adaxial surface of mature leaves (see Skelly 2000, Skelly et al. 1987). Immature leaves seldom exhibit symptoms, whereas premature defoliation of mature leaves may occur on sensitive

species. To the casual observer, these symptoms are similar to those induced by other stresses (e.g., nutrient deficiency, fall coloration, heat stress, as well as certain insects, and diseases). However, the pigmented, adaxial stipple on plants of known ozone-sensitivity (i.e., black cherry or grape) is a reliable diagnostic symptom that can be used to evaluate ozone injury.

On eastern conifers, the most reliable symptom (current-year needles only) induced by ozone is a chlorotic mottle, which consists of small patches of chlorotic tissue interspersed within the green, healthy needle tissue. The mottle usually has a "soft edge" (as opposed to a sharply defined edge) to the individual mottled areas. An extremely sensitive plant may exhibit needle tip browning. However, this latter symptom can be caused by many stresses and therefore is not a reliable diagnostic symptom. Conifer needles older than current-growing season needles are not useful as monitors, since over-wintering and multi-year insect injuries may produce symptoms similar to that caused by ozone. Ozone injury to monocots, such as grasses (i.e., Spartina sp.), is also very difficult to diagnose in the field, as there are many causal agents that can result in tipburn and chlorotic mottle on grasses.

METHODS

Objectives

1). To determine the extent of symptoms characteristic of ozone injury on vegetation in the Okefenokee National Wildlife Refuge

2). To compare injury evaluations with ozone levels monitored near the refuge

General Survey Areas

It had been predetermined that survey sites had to occur in open-areas (such as those occurring along roads or in fields) where ozone-sensitive plant species were found in sunlight and exposed to unrestricted air movement (Anderson et al. 1989; USDA Forest Service, 1990). In addition, a survey area could be chosen if ozone injury was readily apparent on the foliage of one or more plant species growing in an open area.

Prior to the initial 1997 survey (conducted during August 13–18), on-site meetings with refuge personnel, during which refuge maps were viewed and discussed, were used to select general survey areas. Based on these initial discussions, survey areas in 1997 were selected on the north, east/southeast, south, and west sides of the swamp, plus one island actually in the swamp itself. However, results of this initial survey revealed that many tentative survey sites did not contain adequate bioindicator species, or were too shaded. Therefore, site locations were further evaluated and areas that were not suitable were eliminated. General areas visited in 2004 are shown in Figure 1.

Preliminary Selection of Bioindicator Species

An survey of the flora of the refuge was published in 1932 (Wright and Wright 1932). Prior to the 1997 survey, an initial selection of potential bioindicators that might exhibit ozone injury in the survey area was selected from this reference and through discussions with refuge personnel. Of course, many of the plant species tentatively selected grow in scattered localities through the NWR, and would not be present at designated survey areas; likely, they could be found only with the help of refuge biologists or local botanists. In addition, many of these species of known sensitivity are found on the more upland areas, as opposed to the swampy areas. Nevertheless, potential biondicators in or near the swamp included asters (*Aster* spp.), black gum (*Nyssa sylvatica*), blackberries (*Rubus* spp.), blueberries (*Gaylussacia* spp.), flowering dogwood (*Cornus florida*), grapes (*Vitis* spp.), huckleberries (*Vaccinium* spp.), milkweeds (*Asclepias* spp.), mulberry (*Morus alba*, *M. rubra*), pines (*Pinus* spp.), poison-ivy

(*Toxicodendron radicans*), redbud (*Cercis canadensis*), red maple (*Acer rubrum*), sassafras (*Sassafras albidum*), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), viburnums, Virginia creeper, white ash, and winged sumac (*Rhus copallina*). Ornamental and shade tree plantings were examined in selected public areas within the refuge.

It should be pointed out that most true wetland plant species in the swamp community have not been studied with regard to ozone-induced macroscopic symptoms. That is, the ozone-sensitivity of wetland species, as determined by controlled exposures of ozone, is generally unknown.

Monitored Ozone Levels

Ambient ozone concentrations are measured in Florida near the Okefenokee National Wildlife Refuge at two EPA air monitoring locations in Baker County (EPA AIRS site #12-003-0002) and Columbia County (EPA AIRS site #12-023-0002) Florida. These monitoring stations are located 25-30 miles south-southwest of the refuge, and may reflect the approximate levels of ozone entering the refuge and associated Class 1 air quality area.

Prior to the 2004 survey, the annual 2002-2003 ozone levels from these two monitors, presented as cumulative SUM60 values (cumSUM60, ppb.hrs), were examined. As illustrated in Figures 2 and 3, the 2002-2003 ozone levels survey were very low. At the Baker County AIRS monitor, the cumSUM60 ozone values (ppb.hrs) during August reached approximately 11,000 (2002) and 13,000 (2003). At the Columbia County AIRS monitor, the cumSUM60 ozone values (ppb.hrs) during August reached approximately 16,000 in both years. For unknown reasons, the cumSUM60 ozone levels monitored at the Columbia location were greater than those recorded at the Baker County monitor. This is illustrated for 2004 in Figure 4. Although ambient ozone values from both monitors were generally low in 2004, these values are near the threshold levels considered necessary to induce foliar injury on ozone-sensitive vegetation.

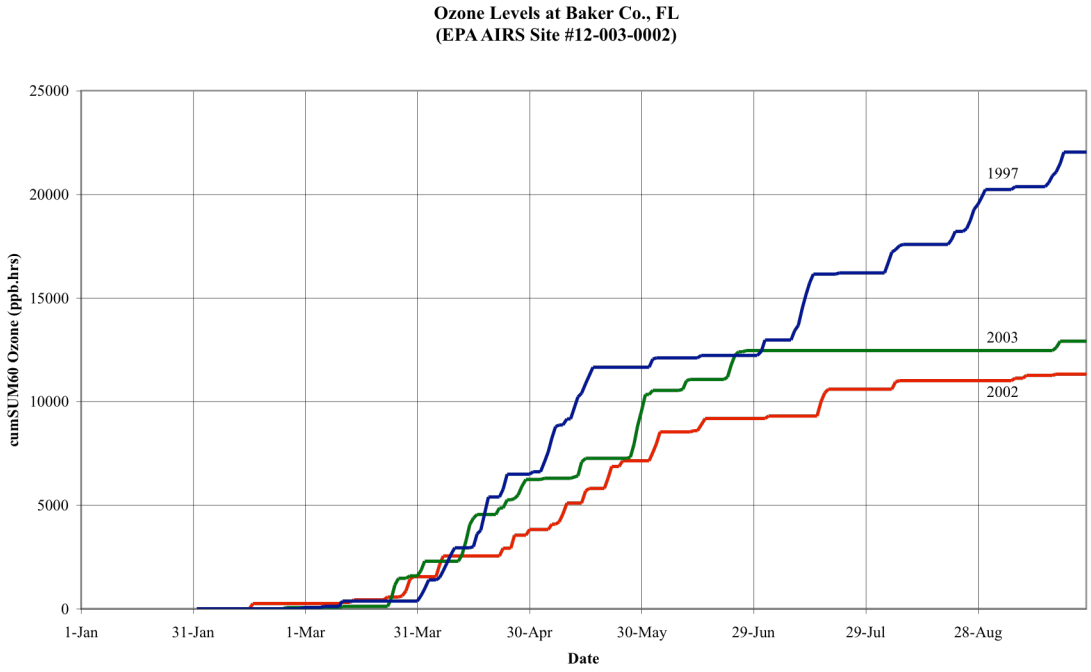

Figure 2. Cumulative doses of ozone greater than 60 ppb (cumSUM60) monitored at Baker County (AIRS #12-003-0002), FL, located approximately 25 miles south-southwest of the Okefenokee NWR. Ozone levels are illustrated during the 2 years prior to the 2004 survey, as well as during the 1997 survey. cumSUM60 is the monthly sum of all hourly ozone concentrations equaling or exceeding 60 ppb; units are ppb.hrs.

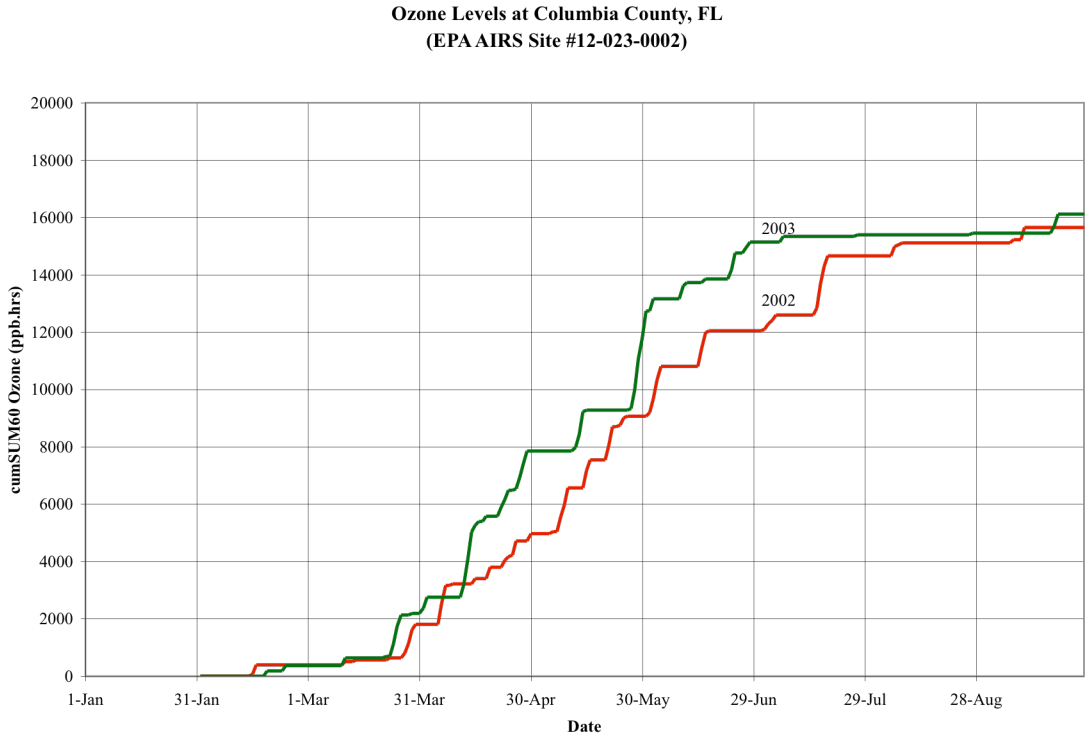

Figure 3. Cumulative doses of ozone greater than 60 ppb (cumSUM60) monitored at Columbia County (AIRS #12-023-0002), FL, located approximately 30 miles south-southwest of the Okefenokee NWR, for 2 years prior to the 2004 survey. cumSUM60 is the monthly sum of all hourly ozone concentrations equaling or exceeding 60 ppb; units are ppb.hrs. The ozone monitor was not operating at this site during 1997, the first year of survey.

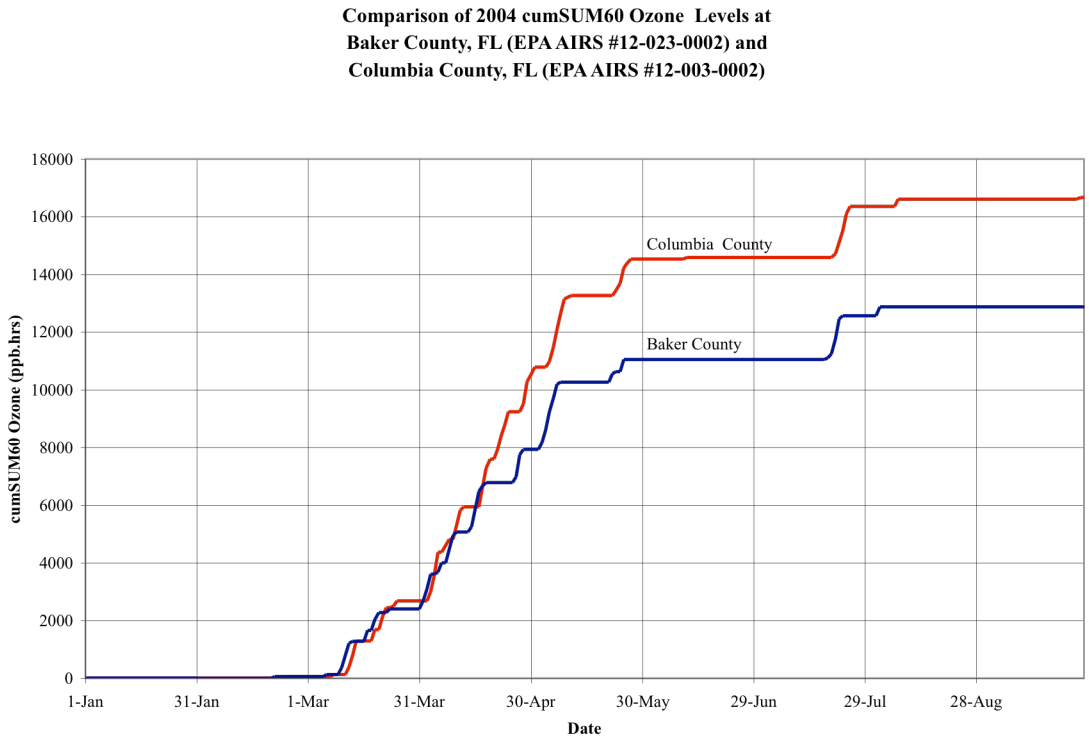

Figure 4. Comparison of 2004 cumSUM60 (ppb.hrs) ambient ozone monitored at Baker County (AIRS #12-003-0002) *vs* Columbia County (AIRS #12-023-0002), FL; both monitors are located 25-30 miles south-southwest of the Okefenokee NWR.

Surveys Dates and Specific Locations

The Okefenokee National Wildlife Refuge was surveyed on August 26-29, 2004. In 1997 it had been surveying during August 13-18. Because the 1997 survey revealed few indicator species within the interior of the refuge, only vegetation growing only along edges of the NWR was examined in 2004. The approximate location of survey areas was based on the 1997 survey. Four areas were deemed suitable for the 2004 ozone injury surveys. (Although these were open areas, there was often a lack of bioindicators present). These survey locations were designated as: Refuge Headquarters, Forest Management Compartment 5, Stephen Foster State Park, and Forest Management Compartment 1. In addition to these locations, vegetation was examined as the investigator traveled the roads from location to location.

Severity Rating

Each broadleaved plant evaluated for ambient ozone injury had to have foliage within reach; that is, trees were not climbed nor were pole pruners used. The ForestHealth Expert System had been used to train the investigator in estimating the amount of stipple on a leaf.

For broadleaved tree species, the investigator uses following system to rate bioindicator plants during such refuge surveys. The percentage of ozone injury is estimated on the oldest leaf on each of four branches, and the average value recorded. Then, the next oldest leaf is evaluated, and so on, until the five oldest leaves have been rated. For each herbaceous plant, each of the five oldest (basal) leaves of the plant is examined and the average percent stipple recorded. Each of the oldest five leaves on the current woody growth (canes) of vines is rated and the average percent stipple recorded. On all species, only adaxial leaf surfaces are evaluated. Symptom severity on the adaxial surface of each evaluated leaf is estimated by assigning severity classes, based on the percentage of surface injured: 0, 5, 20, 40, 60, 80, 95 and 100%. If suitable plant material is present, and weather conditions adequate to permit useful photography, digital images and/or slides are taken and sent to the FWS Air Quality Branch in Denver.

RESULTS

Final Selection of Bioindicator Species

The final selection of bioindicator species for this 2004 survey was made on-site in the field. Most plant species in wetlands such as the swamp community have not been carefully studied with regard to ozone-induced macroscopic symptoms. That is, the ozone-sensitivity of wetland plants as determined by controlled exposures of ozone is generally unknown, and it is dangerous to attribute ozone as the cause of various foliar discolorations on untested species. However, it was deemed important to evaluate even unknown species, because of their possible importance in the wetlands ecosystem, for the presence or absence of classic dark adaxial stipple, the most useful diagnostic criterion for ozone injury on broadleaved plants.

Foliar Symptoms

Refuge Headquarters (= Forest Management Compartment 3)

Near the refuge headquarters on the eastern edge of the refuge (Figure 1, Location 2), vegetation was examined in the large open area near the boat launch. Many ornamentals had been planted in this area. Species examined included American sycamore (2), muscadine grape (*Vitis muscadine*) (10), longleaf pine (*Pinus palustris*) (4), redbud (10), *Rubus* spp. (20), and sweetgum (5). The number in parentheses indicates the number of individual plants examined. There was no ozone-induced stipple on the two American sycamores growing at this location. These two individual trees had exhibited definite ozone stipple in 1997. Longleaf pines did not have a chlorotic mottle in 2004, resembling that caused by ozone. There was no ozone injury on redbud, grape, or sweetgum. Some of the *Rubus* species had red foliage; however, this symptom was not a definitive stipple and was likely be induced by other stresses.

Forest Management Compartment 5

A few *Rubus* spp. were turning red at this survey location (Figure 1, Location 3) at the southern edge of the refuge. This discoloration somewhat resembled ozone-induced injury on a few individual plants, but any stipple that might be present was confounded by the discoloration and was not rated. Thirty sweetgum plants were evaluated, but did not exhibit ozone injury. Many hundreds of other individual broadleaved plants were also examined. Adaxial stipple, typical of that induced by ozone, was not observed on any species at this location.

Stephen Foster State Park

At this location in the east-central part of the refuge (Figure 1, Location 4), hundreds of plants were examined. Ozone injury was not observed on *Rubus* spp. (40), sweetgum (20), muscadine grape (20), or on hundreds of other individual plants of other species. The number in parentheses indicates the number of individual plants examined. Most plants in this area were not injured by ozone. In 1997, many individual, roadside plants of an unknown species were observed to have leaf injury similar to that caused by ozone. However, this species could not be found in 2004. It may have been removed during mowing.

This state park is the best area within the NWR that should be considered for future surveys to document the presence or absence of ozone-induced injury on vegetation.

Okefenokee State Park and Tourist Area (= Forest Management Compartment 1)

At this location along the northern edge of the refuge near the gate leading into the Okefenokee Park and tourist area (Figure 1, Location 5), plants were examined. Ozone injury was not observed on any species, including *Rubus* (20), Virginia creeper (5), Chinese tallow tree (10), sweetgum (10), and muscadine grapes (10). There was a very slight, general reddening of foliage on *Rubus* spp.

DISCUSSION AND SUMMARY

There are no ozone monitors located within the Okefenokee NWR itself. The two closest EPA AIRS monitors are located in Baker County and Columbia County (Florida), 25-30 miles south-southwest of the refuge. Lack of monitors within the refuge is unfortunate, as monitors located 25-30 miles away may not reflect ambient ozone levels within the refuge. To further complicate the issue, the cumSUM60 ozone levels at the Columbia County location were greater than those recorded at the Baker County monitor (Figure 4), for unknown reasons. This difference in monitoring data makes it difficult to relate ambient ozone levels to field symptoms. Nevertheless, cumSUM60 ozone levels at both EPA AIRS locations were quite low in 2004 (Figures 2-4), so we might assume that ozone levels were also low within the nearby Okefenokee refuge. During the years (2002-2003) immediately prior to this latest survey, ambient ozone concentrations were also fairly low. The low levels of ozone are not surprising, due to the fairly remote location of the Okefenokee and lack of upwind point sources that may emit ozone precursors.

Even so, the monitored ozone concentrations, and assumed ozone levels within the refuge, are near the known threshold capable of causing ozone injury to sensitive species of vegetation. The ambient ozone data monitored at the two nearest EPA AIRS air monitoring stations can be used to approximate year-to-year comparisons regarding the relative amounts of ozone experienced by vegetation within the refuge. By the time of the 2004 survey, the cumSUM60 ozone levels had exceeded 12,000 ppb.hrs at the Baker County monitor and 16,000 ppb.hrs at Columbia County (Figure 4). However, since ozone injury was not observed during 2004, either the ambient ozone levels were slightly too low, few sensitive plant species were present, environmental conditions were not conducive for ozone injury to occur, or some interaction occurred among these factors to limit ozone injury.

In contrast, ozone injury had been observed within the refuge during the 1997 survey. Thus, ambient ozone levels (and conducive environmental conditions) had been sufficient in 1997 to cause injury to vegetation within the boundaries of the Okefenokee NWR. The 1997 ozone concentrations that caused plant injury within the refuge can be approximated from those measured at the Baker County EPA AIRS monitor (Figure 2). (The EPA AIRS monitor at Columbia County was not operating in 1997). During the August 13-18, 1997 survey, the

cumSUM60 ambient ozone levels at the Baker County monitor was greater than 16,000 ppb.hrs, exceeding the threshold for plant injury (Figure 2).

However, long-term monitoring datasets are needed to understand the complex relationship between foliar symptoms, ambient ozone, and environmental conditions (such as droughts) in our parks and refuges. For example, drought and resultant plant water stress can result in stomatal closure and reduced uptake of ozone by vegetation, resulting in less ozone injury during dry years, despite high ambient ozone levels. However, most areas surveyed in the Okefenokee were wet in 2004. The drought factor is not likely related to the paucity of ozone injury observed during the 2004 survey.

The 1997 and 2004 surveys revealed few ozone-sensitive bioindicators in the refuge, making it difficult to record the incidence and severity of ozone injury on bioindicators. However, some ozone-sensitive plant species were encountered, including flowering dogwood, redbud, sweetgum, and winged sumac. Generally ozone-sensitive species did not exhibit ozone injury during these surveys. Occasional *Rubus* spp. had red foliage, but this was not likely caused by ozone. Ozone injury did occur on the one of two American sycamores evaluated in 1997. Sycamore is very sensitive to ozone and is an excellent bioindicator, but only two individual plants were encountered during the surveys.

Stipple, typical of that caused by ozone, was not observed on individuals of most unknown species examined. However, one unknown plant species in the Stephen Foster State Park appeared to be very sensitive to ozone in 1997, but could not be located in 2004. Little is known regarding the sensitivity of most other swamp or wetland plants to ozone. An important missing database in the environmental field is the lack of knowledge regarding the incidence and severity of ozone injury to wetlands vegetation, and the inherent ozone-sensitivity of species of concern in these critical landscapes.

In summary, the results of the two surveys (1997 and 2004) revealed that ozone injury on vegetation occurs within the boundaries of the Okefenokee Swamp National Wildlife Refuge, which encompasses a Class I air quality area. Although no such injury occurred in 2004, there was ozone injury in 1997 on an unknown woody species within the refuge. The FWS should consider surveying the Okefenokee NWR again in the future to help determine the threshold of ambient ozone needed to cause foliar injury on southern plant species in such remote locations.

In addition, the refuge should consider determining the level of mercury within vegetation in the Okefenokee NWR, since Florida has among the highest levels of mercury in the USA.

These results should prove useful to the FWS when making air quality management decisions, including those related to the review of Prevention of Significant Deterioration (PSD) permits.

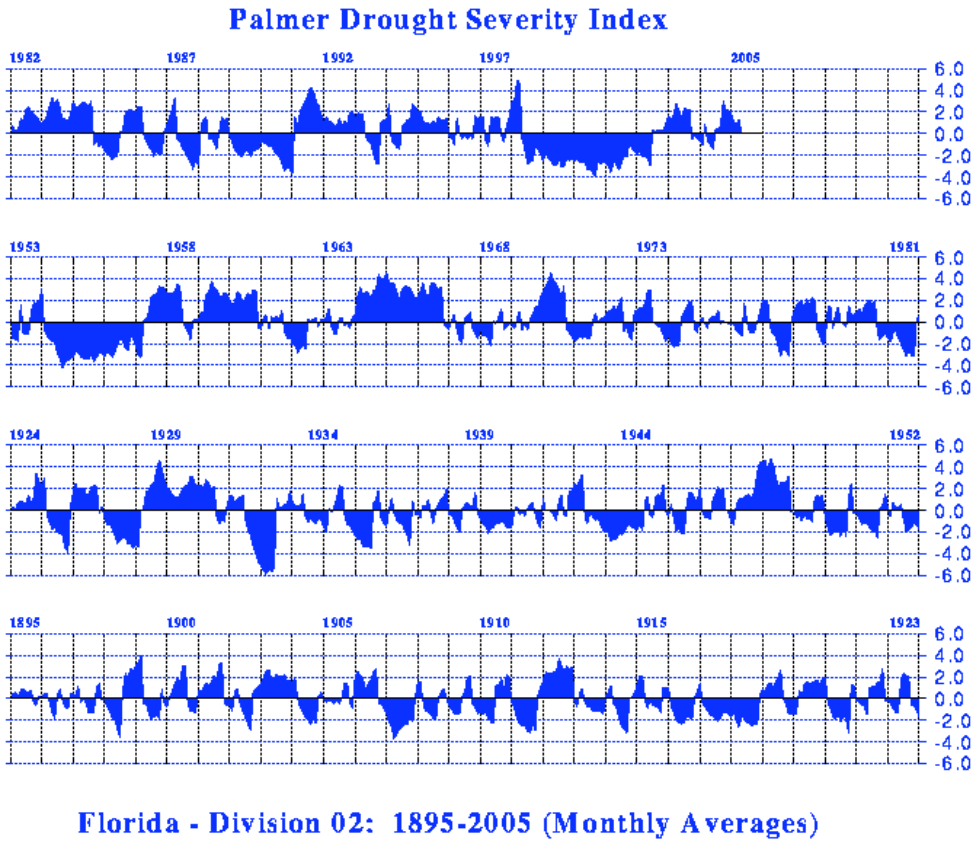

Figure 4. Palmer Drought Severity Index (PDSI) for northeastern Florida during 1895-2004. The horizontal line at "0" is considered normal moisture levels. Areas above the line represent adequate or surplus moisture for normal plant functioning, whereas areas below the line represent potential water stress. A drought severity index of -3 is generally considered to be a severe drought, likely inducing stomatal closure and reducing ozone uptake**.** The figure illustrates that a prolonged drought occurred in during mid-1998 to mid-2002. The first year of survey (1997) was moderately wet; 2004 was wet.

RELATED LITERATURE

Anderson, R. L., C. M. Huber, R. P. Belanger, J. Knighten, T. McCartney, and B. Book. 1989. Recommended survey procedures for assessing on bioindicator plants in Region 8 Class 1 Wilderness areas. USDA Forest Service, Forest Pest Management, Asheville Field Office Report 89-1-36, 6 pp.

Conkling, B. L. and G. E. Byers (eds.). 1993. Forest Health Monitoring Field Methods Guide. Internal Report. US EPA, Las Vegas, NV

Davis, D. D. 1984. Description of leaf injury caused by gaseous air pollutants. pp. 77-82 In: Davis, et al. (ed.). Proc. Sym. Air Pollut. and Productivity of the Forest, Wash., DC. Oct. 4-5, 1983. Pub. by Izaac Walton League, Wash., DC, 344 pp. .

Davis, D. D. and J. B. Coppolino. 1976. Ozone susceptibility of selected woody shrubs and vines. Plant Dis. Rptr. 60:876-878.

Davis, D. D. and J. M. Skelly. 1992. Foliar sensitivity of eight eastern hardwood tree species to ozone. J. Water, Air, Soil Pollut. 62:269-277.

Davis, D. D. and R. G. Wilhour. 1976. Susceptibility of woody plants to sulfur dioxide and photochemical oxidants. E.P.A. Ecol. Res. Series EPA 600/3-76-102, 70 pp.

Davis, D. D., J. R. McClenahen, and R. J. Hutnik. 2001. Use of an epiphytic moss to biomonitor pollutant levels in southwestern Pennsylvania. Northeastern Naturalist 8:379-392.

Davis, D. D., J. R. McClenahen, and R. J. Hutnik. 2002. Selection of a biomonitor to evaluate mercury levels in forests of Pennsylvania. Northeastern Naturalist 9:183-192.

Davis, D. D., A. Millen, and L. Dochinger (ed.). 1984. Air pollution and productivity of the forest. Proc. Sym. Air Pollut. and Productivity of the Forest, Wash., DC. Oct. 4-5, 1983. Pub. by Izaac Walton League, Wash., DC, 344 pp.

Davis, D. D., J. M. Skelly, and B. L. Nash. 1995. Major and trace element concentrations in red oak, white oak, and red maple foliage across an atmospheric deposition gradient in Pennsylvania. Proc. Tenth Annual Centr. Hdwd. Conf. Morgantown, WVA, USDA Forest Service Tech. Bull. pp 188-195.

Davis, D. D., D. M. Umbach, and J. B. Coppolino. 1981. Susceptibility of tree and shrub species and response of black cherry foliage to ozone. Plant Dis. 65: 904-907.

Davis, D. D., F. A. Wood, R. J. Hutnik, G. C. Weidersum, and W. R. Rossman. 1984. Observations around coal-fired power plants in Pennsylvania. Forest Wissen. Centralblatt 103:61-73.

Jensen, K. F. and L. S. Dochinger. 1989. Response of eastern hardwood species to ozone, sulfur dioxide, and acidic precipitation. J. Air Pollut. Control Assoc. 39:852.

Pye, J. M. 1988. Impact of ozone on the growth and yield of trees: A review. J. Environ. Qual. 17:347-360.

Rosenberg, C. R., R. J. Hutnik, and D. D. Davis. 1979. Forest composition at varying distances from a coal-burning power plant. Environ. Pollut. 19:307-317.

Skelly, J. M. 2000. Tropospheric ozone and its importance to forests and natural plant communities of the northeastern United States. Northeastern Naturalist 7:221-236.

Skelly, J. M., D. D. Davis, W. Merrill, and E. A. Cameron (Eds.). 1987. Diagnosing injury to eastern forest trees. College of Agric., Penn State Univ., 122 pp.

Umbach, D. M. and D. D. Davis. 1984. Severity and frequency of SO_2-induced leaf necrosis on seedlings of 57 tree species. For. Sci. 30:587-596.

van Haut, H. and H. Stratmann. 1969. Color-plate atlas of the effects of sulfur dioxide on plants. Verlag W. Girardet, Essen, W. Germany, 206 pp.

Wood, F. A., R. J. Hutnik, D. D. Davis, G. C. Weidersum, and W. R. Rossman. 1982. Effects of large coal-burning power plants on vegetation in western Pennsylvania. Pres. 75th Annu. Meet. APCA, New Orleans, Preprint No. 82-67.7.

Wright, W. A. and A. A. Wright. 1932. The habitats and the composition of the vegetation of Okefinokee [sic] Swamp, Georgia. Ecol. Monographs 2:109-232.