Smoke problems were of concern to Londoners in the 17th century. Palls of black smoke, from the burning of soft coal in many homes across London, covered the city during calm winter days. This was regarded only as a nuisance at that time.

During the latter half of the 19th century, the smelting of ores became widespread throughout the industrialized world. The early smelters were often large pits in the ground, where the ore was smelted over open beds of coal. Gases escaping from such an operation were released directly to the atmosphere at ground level and could affect sensitive plant and animal life in the vicinity.

Research in Europe during the late 19th century pointed to sulfur dioxide as the most likely toxicant in the plume from the smelter. Sulfur dioxide was released from the burning of fuel and from sulfide oxides in the ores. Injury to plants was often the first evidence of toxic levels of sulfur dioxide in the atmosphere.

During the early part of this century, severe leaf injury to many plant species growing in the vicinity of several smelters in the United States was identified as sulfur dioxide injury. One of the most intensively studied smelters was in the copper basin of eastern Tennessee, often referred to as Copper Hill or Duck Town. After years of open pit burning at Copper Hill, all vegetation within a half mile of the smelter was lost. At a greater distance, trees and shrubs were gone and only a band of hardy grasses remained. A secondary effect of denuding the landscape was the severe erosion that resulted.

Even after the open pit smelting was stopped in the early 20th century and a smelter with low stacks was constructed, injury to vegetation around the new plant continued, and plants did not recover. The type of injury evident at Copper Hill is no longer found in the United States due to increasing environmental sensitivity of the U.S. public and to changing corporate management practices.
Which Pollutants Harm Plants?

Although many gases toxic to plant life were released from a multitude of industrial operations during the early days of industrial development, only sulfur dioxide received wide concern among scientists until the early 1940's. At that time, increasing evidence of injury from hydrogen fluoride was associated with the increase in aluminum smelters, where fluoride compounds are used in processing ores. Since then, considerable research has gone into studying the effects of gaseous fluoride on plant health. During the 1960's, concern for both sulfur dioxide and fluoride diminished because control technologies were developed to collect these gases from industrial plants, lowering emissions enough so they caused little or no harm to sensitive vegetation.

In the late 1940's and into the 1950's, another type of injury to many plant species was observed throughout the Los Angeles Valley in California. This was related to the increasing severity of the "smog" problem that was becoming more apparent in the valley during this time. Scientists finally related the problem to a group of chemicals that had strong oxidizing characteristics. In 1958 ozone was identified as the most important of these oxidants, and ozone's effects on numerous sensitive crop species were subsequently confirmed.

In 1961, a second plant toxicant was identified as PAN (peroxyacetyl nitrate—a stronger oxidizing chemical than ozone). Subsequently, ozone was identified as the cause for plant injury throughout the United States and in other industrialized countries. Although plants are more sensitive to PAN than to ozone, PAN is not considered a national problem because the concentrations are too low in most areas of the country to injure sensitive vegetation. However, some scientists believe that even small quantities of PAN probably enhance the reported widespread impacts of ozone on many crop species.

The effect of acid rain on trees on White Face Mountain in New York State. Acid rain, combined with other sources of atmospheric and ground pollution, triggered the damage.

Bernie Yee/USDA 88BW0051-24A
Air Pollutants Now
Today, hundreds of pollutants are emitted into the air in the industrialized and developing world. These are divided into primary and secondary pollutants. Primary pollutants are emitted directly into the atmosphere from sources such as power plants, factories, automobiles, and residential furnaces. There are also natural sources of pollutants, such as forest fires and volcanic eruptions. Primary pollutants include sulfur dioxide, nitrogen oxides, ethylene, other volatile organic compounds, and heavy metals.

Secondary pollutants form when certain primary pollutants undergo chemical changes in the atmosphere. The two groups of secondary pollutants of most concern to crop and forest resources are photochemical oxidants and acidic deposition (popularly called acid rain). Photochemical oxidants, such as ozone, form in the atmosphere when the primary pollutants (volatile organic compounds and nitrogen oxides) react in the presence of sunlight. Acidic deposition forms when nitrogen oxides and sulfur dioxide react with oxidants and moisture in the atmosphere to form nitric acid.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Primary or secondary pollutant</th>
<th>Form</th>
<th>Major source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone (O₃)</td>
<td>Secondary</td>
<td>Gas</td>
<td>Product of chemical reactions in the atmosphere</td>
</tr>
<tr>
<td>Acidic deposition (sulfates and nitrates)</td>
<td>Secondary</td>
<td>Particulate</td>
<td>Product of chemical reactions in the atmosphere</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>Primary</td>
<td>Gas</td>
<td>Power generation, smelter operation</td>
</tr>
<tr>
<td>Nitrogen dioxides (NOₓ)</td>
<td>Primary and secondary</td>
<td>Gas</td>
<td>From direct release and atmospheric transformation</td>
</tr>
<tr>
<td>Hydrogen fluoride (HF)</td>
<td>Primary</td>
<td>Gas/Particulate</td>
<td>Superphosphate production, and aluminum smelters</td>
</tr>
<tr>
<td>Ethylene</td>
<td>Primary</td>
<td>Gas</td>
<td>Combustion, natural causes</td>
</tr>
</tbody>
</table>
and sulfuric acid; these are usually associated with wet deposition.

Ozone is the most important pollutant causing damage to crops and forests in the United States and will thus be the primary focus of this chapter. However, with the increase in large power plants over the past 20 years and the advent of high stacks, acid rain—resulting from sulfur dioxide and nitrogen oxides—has become of greater concern from a regional and national perspective. Some research, using expected levels of sulfur dioxide in the atmosphere, suggests that crop damage from ozone may increase slightly by the added sulfur dioxide; this could also be true for some sensitive forest species. The concern for acidic deposition, although a regional problem, has lessened following the intense studies on acidic deposition carried out during the 1980’s. We touch briefly on wet deposition associated with acidic substances.

A final pollutant of regional significance is ethylene. Ethylene is a normal by-product of plant
metabolism and is considered a plant growth hormone. It is also a major emission from the automobile and can reach plant-damaging levels in the atmosphere. However, the information available on ethylene is too uncertain for consideration in this chapter.

Table 1 lists the air pollutants mentioned above, shows whether they are released directly from the source (primary pollutants) or are formed in the atmosphere (secondary pollutants), indicates the form of the pollutant, and lists the major sources.

**The Air Quality System**

We used to think that air pollution was just a city problem. Now, we know that pollutants can be transported hundreds of miles and can be found in elevated concentrations in rural and forested areas. The atmosphere can be thought of as an “ocean of air.” Like an ocean of water providing dissolved nutrients and oxygen to aquatic plants, the ocean of air provides chemicals essential to terrestrial plants and animals. Like an ocean, the atmosphere also has the ability to spread, mix, and transport in its currents any polluting chemical put into it. Although pollutants emitted into the atmosphere eventually are deposited, they can travel hundreds of miles before coming to the ground. Exactly how these pollutants affect our agricultural and forest lands when they do reach the ground remains uncertain, but studies have provided some evidence of their effects on plants, and research continues.

For the assessment of crop and forest losses, a knowledge of both natural and synthetic sources of pollution is critical. This information permits the determination of maximum loading of the atmosphere for any given locality. Synthetic sources include mobile sources, such as automobiles, associated with pollutants of regional concern, as well as stationary or point sources. Transport and transformation processes must be understood to determine the distance a pollutant can be transported and the rate of loss or formation of different pollutants in the air masses. The concentration of gases in the atmosphere is related to the trace components, air movement, and atmospheric stagnation periods. Both ozone and sulfur dioxide can be transported long distances and cause problems in rural as well as urban areas.

To understand the effects of ozone or sulfur dioxide on crop or forest productivity, we must know:

- The atmospheric concentration to which the plant is exposed (the exposure concentration),
- The duration of each exposure, and
- The number of exposures during the growing season.
These three factors determine the exposure dose, which is the air quality unit that links the atmospheric scientist, the plant scientist, and the control official. The exposure dose is the air quality measure necessary to set an air quality standard. It can be used to determine gas uptake by the plant and is essential for a regional assessment.

Air pollutants are removed from the atmosphere by both wet and dry deposition processes. Dry deposition of gases to plants occurs through small openings in the leaves called stomates. Ozone, sulfur dioxide, and other gaseous pollutants are taken up by plants in this way. When gases enter leaves they can cause a variety of physiological and/or biochemical responses. Depending on the concentration in the leaf, the effects may or may not affect crop or forest production.

To understand mechanisms by which air pollutants affect plant productivity, the effects on leaves must be understood. For assessment purposes, it is necessary only to relate reduction in productivity (yield of crops) with the exposure concentration of either ozone or sulfur dioxide. However, an understanding of mechanisms will improve our ability to predict the effects of different pollutant levels on crop or forest productivity.

Rain, snow, and dew are three wet deposition processes that deposit pollutants, such as acidic substances, on leaf surfaces. Although these substances can enter the leaf, the amount entering the leaf is less than from dry deposition. These substances are also less toxic than ozone or sulfur dioxide but can add to the impact of those two gases.

Symptoms of Leaf Injury
Visible leaf injury occurs as patterns of color change or dead tissue that result from major physiological disturbances in plant cells. Visible injury usually is classified as acute or chronic, depending on the length of exposure and the severity of the injury. Acute injury from both ozone and sulfur dioxide initially shows on the intact leaf as a slightly water-soaked or bruised appearance. The injury is caused by disruption of cell membranes which, if suffi-
ciently severe, may result in the loss of cell contents and death of the cell. The affected areas generally dry out, producing necrotic patterns (dead leaf tissue) that tend to be characteristic of ozone or sulfur dioxide injury.

Chronic injury may be mild or severe. Initial disruption of normal cellular activity may be followed by leaf yellowing (chlorosis, the loss or reduction of the green plant pigment, chlorophyll) and/or other color or pigment changes; cell death may eventually occur. Chlorosis is a very common and nonspecific symptom in plants, somewhat analogous to anemia in animals. Other colors often appear from pigments normally masked by the green of the chlorophyll. Chronic injury may look like normal fall coloration (senescence) with or without loss of leaves.

Chronic injury patterns are generally not characteristic of a given pollutant and are easily confused with symptoms associated with other stresses. Chronic symptoms associated with ozone and sulfur dioxide injury may aid injury diagnosis but are not definitive for either gas.

**Ozone:** Broadleaf plants show upper-surface, red-brown spots (stipple); bleached tan to white areas (fleck); small irregular bifacial collapsed (necrotic) areas that may join to form irregular necrotic blotches; chlorosis and early fall coloration. Grasses show scattered necrotic areas (fleck) on both leaf surfaces; sometimes larger lesions or necrotic streaking may occur. Conifers may show brown-tan necrotic needle tips with no separation between dead and healthy tissues.

**Sulfur Dioxide:** Broadleaf plants show irregular necrotic areas bleached white to tan or brown which can occur on leaf margins or between veins of the leaf; chlorosis may be associated with necrotic areas, or a general chlorosis of older leaves may develop; diffuse to stippled colors ranging from white to reddish-brown have been observed.

Grasses show irregular, bifacial, necrotic streaking between larger veins that is bleached light tan to white; chlorosis usually is not pronounced. Conifers may show brown necrotic tips of needles often with a banded appearance; generally chlorosis of adjacent tissue occurs; needles of the same age are uniformly affected.

**Impacts of Pollutants on Forests**

Trees in forests are part of a complex, interdependent community of plants and animals. Each living organism in the community depends on others. The health of a forest also depends on certain nonliving factors, such as soil quality and rainfall. The chemistry and quality of the air are vitally important. Trees obtain nutrients from the soil through their roots; although it is less well
known, trees also obtain nutrients from the air. Some nutrients are taken directly out of the air and into leaves; others fall onto the soil and are taken up by roots. Often, rain and clouds carry nutrients into the forest. Pollutants in the air and water can enter forests through the same pathways as nutrients. Most commonly, these nutrients enter into the forest through precipitation.

Normal precipitation contains many chemical compounds, including some of the nutrients plants need. Precipitation also can carry pollutants into forests. Trees may be exposed to air pollution in many forms, because pollutants can be brought into forests in gaseous or solid forms as well as dissolved in precipitation. Toxic metals (such as lead and cadmium) and aluminum, which are present in trace amounts in polluted air, can inhibit the uptake of needed nutrients and, on rare occasions, damage roots. Such damage increases a tree's susceptibility to winter injury.

Forest declines and recoveries have been reported for at least several hundred years. Declines can occur from natural causes in areas where air pollution levels are very low. Determining if a decline is due to natural causes or to human causes—such as air pollution—can be difficult because symptoms from various causes often look the same. Furthermore, forest declines are caused by the interaction of more than one stress factor.

**Other Effects of Ozone and Sulfur Dioxide**

Both ozone and sulfur dioxide can affect various processes in sensitive plants at concentrations causing light to intense leaf injury. Research has shown that photosynthesis is a primary plant process affected by both gases. This means that the basic food-producing mechanism in the plant is affected. At the lowest level of effect, there is evidence in some plants that the reduced level of assimilate moves preferentially to new shoot growth at the expense of root growth. However, both shoot growth and yield of sensitive crop and tree species can be reduced by either gas.

Changes in growth rate can occur when plants are exposed during early vegetative growth, but normal growth resumes shortly after the exposure ends. Changes in the quality of the usable product can occur but are not always important. Changes in levels of plant metabolites have been found from exposures to each gas. These changes have been found for many enzyme systems in sensitive plants and in some more resistant plants. Although not all mechanisms of injury for either gas are understood, it is generally accepted that stomatal control of gas...
exchange and physiological factors play a role in plant sensitivity to both gases.

Variation in sensitivity to ozone or sulfur dioxide can be found among species and even among cultivars of single species. Most research has addressed annual field and vegetable crops, so our knowledge of perennial and woody species is more limited. However, we know that many woody plant species show sensitivity to either of these gases. In general, field corn and sorghum are considered to be two of the crops most resistant to either gas. Although the sensitivity of crop species to yield loss from sulfur dioxide is not as well documented as for ozone, some cotton, alfalfa, soybean, and tobacco cultivars are known to be very sensitive to sulfur dioxide.

Some of the most important crops sensitive to ozone are soybeans, cotton, peanuts, tobacco, clover, alfalfa, dry beans, garden beans, potatoes, watermelons, other melons, and sugar beets. In all species studied, there is good evidence of resistance in the gene pool.

Many biological and physical factors, in addition to cultivar and species differences, affect the response of plants to ozone and sulfur dioxide. Biological factors such as plant diseases and insects can affect plant response. Environmental factors such as temperature, light, humidity, nutrition, and soil moisture can also affect plant response. Our knowledge of the effects of these factors on plant response to the two pollutants is not complete. A full understanding of their impact requires understanding the interrelationships among biological stresses and plant response to both ozone and sulfur dioxide.

Recent research indicates that the current level of ozone in rural areas causes growth and yield reductions in sensitive species, where concentrations are below the current ozone standard of 0.12 parts per million (ppm) for 1
hour. Sulfur dioxide concentrations in agricultural areas away from point sources rarely exceed 0.01 ppm for extended periods of time. Research to date suggests that regional concentrations of sulfur dioxide at or below these levels should not cause yield decreases in sensitive crop species. However, in the presence of ozone, these levels of sulfur dioxide may increase losses associated with ozone alone.

Effects of Acidic Deposition

Acidic deposition has been narrowly defined as the wet deposition (in rain, snow, or dew) of acid substances (nitric and sulfuric acids). A broader and more widely accepted definition includes the wet or dry deposition of acids or acidifying substances. The broader definition includes sulfur dioxide and nitrogen oxides in addition to the strong acids. In its broadest context, it has enveloped ozone, since ozone is part of the atmospheric acidifying process. However, we have confined this section to a discussion of wet deposition of acid substances, principally from rainfall.

The information on acid rain is not as extensive as that for ozone or sulfur dioxide. The current body of research indicates that acid deposition at current levels is not responsible for significant agricultural crop yield reductions. Soybeans are the only crop that would be adversely affected by rain that was slightly more acidic than current levels.

These negative impacts are counteracted by a “fertilization” effect, since sulfur and nitrogen deposition in acid rain provide part of the plant’s nutrient requirements. Adam, Callaway, and McCarl estimated a $140 million benefit in 1980 dollars for a 50-percent reduction in acid deposition, when they excluded the “fertilization” effect. When the “fertilization” effect was accounted for, they estimated net benefits of reducing acid deposition to be negligible to negative.

This beneficial fertilizer effect is not as clear for forests. Excess nitrogen may be taken up through the roots or foliage of trees. Although nitrogen is an essential nutrient for plant life, excess nitrogen can disturb the nutrient balance or disrupt the physiology of the plant. We also know that acid deposition is not as directly damaging to forests as we once thought it might be. But acid deposition does cause changes in soil chemistry that might adversely affect forests over the long run. Similarly, acidic cloud water may be working together with other factors to further stress red spruce in high-elevation forests in the Northeast. Research indicates that ozone interferes with this tree’s photosynthesis process.
Assessing Impacts of Ozone on Crop Production

In order to assess the economic effect of ozone on crop production, researchers study the response of the plant part intended for human use—the yield component. Local, regional, or national assessments of crop losses require three types of information: 1) a crop census indicating which crops are grown and their yields within a geographic unit such as a county or State, 2) an air quality data base for use in estimating the crop exposure dose, which covers the same geographic unit as the crop census, and 3) a crop response equation relating crop yield to the exposure dose.

USDA provides data on crop production on a county level every 5 years. In addition, crop production and yield data are reported each year on a State basis. These yield and acreage figures are averaged across cultivars to produce a countywide or statewide census for each crop. The county yield data for each crop are used in assessing the effects of ozone on crop yields.

The U.S. Environmental Protection Agency (EPA) has a large ozone data base that was used to develop the exposure dose on a county level.

Ozone exposure dose-crop response equations have been developed for a large number of crop species and cultivars through the National Crop Loss Assessment Network (NCLAN) program.

The National Crop Loss Assessment Network (NCLAN)

EPA initiated the NCLAN program in 1980 to help assess the impact of ozone on crop production. USDA’s Agricultural Research Service was involved in planning and carrying out research in cooperation with EPA throughout the program. Four primary and three secondary regional sites were established to conduct field studies from 1980 through 1986. Forty-four field experiments on 17 crop species (38 cultivars and three genetic crosses) were run to determine the impact of ozone on growth and yield. Plants were grown under field conditions and exposed to different ozone exposure doses in open-top field chambers.

Thirty-five of the experiments included factors other than ozone, for example low soil moisture, sulfur dioxide, several cultivars, method testing, and detailed growth studies.

Yield loss estimates were obtained from crop response equations that reported yield loss on a percentage basis. The exposure dose was the seasonal mean of either the 7-hour or the 12-hour daily exposure period. The ozone monitoring data across the United States were interpolated by a technique called kriging to give estimated county level ozone...
exposure doses, and crop yields on a county basis were obtained from USDA. National yield losses were estimated from the models and were used in an economic model to derive estimated producer and consumer benefits with increasing and decreasing ozone concentrations.

EPA used the results from the NCLAN assessment program in considering a revision of the ozone air quality standard. The current standard is still 0.12 ppm for 1 hour, but longer term standards have been suggested based on the NCLAN data.

Estimated yield losses at current ozone exposure doses in the United States are shown in table 2 for several important agricultural crops. Soybeans were the most intensively studied crop, with 14 experiments using 9 different cultivars performed during the 7 years of the program. Cotton, with five studies and four cultivars, was the next most intensively studied of the major crops.

Cost to American Agriculture

Based on early crop response data, a number of regional and national economic assessments were made during the 1980's. Regional estimates found that crop losses due to ozone were about $30 million for Minnesota and about $670 million for the Corn Belt. National estimates based on different

<table>
<thead>
<tr>
<th>Crop</th>
<th>Percent yield loss under current ozone stress¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>7.1</td>
</tr>
<tr>
<td>Corn</td>
<td>3.3</td>
</tr>
<tr>
<td>Cotton</td>
<td>14.0</td>
</tr>
<tr>
<td>Forage</td>
<td>7.7</td>
</tr>
<tr>
<td>Peanuts</td>
<td>12.5</td>
</tr>
<tr>
<td>Sorghum</td>
<td>1.7</td>
</tr>
<tr>
<td>Soybeans</td>
<td>15.3</td>
</tr>
<tr>
<td>Tobacco</td>
<td>11.1</td>
</tr>
<tr>
<td>Wheat</td>
<td>5.8</td>
</tr>
</tbody>
</table>

¹The percent losses shown are predicted losses based on a seasonal 7hr/day or 12hr/day average ozone concentration of 0.05 ppm. Actual seasonal averages across the U.S. for these time periods range from 0.035 to 0.065 ppm.
groups of crops ranged from $1.2 to $3.0 billion. Corn and soybeans were included in all of these estimates.

Early NCLAN data were used to develop an economic model from which the effects of reduced and increased levels of ozone on producer and consumer costs could be estimated and a total cost calculated. The economic estimates showed benefits of reduced ozone to both producers and consumers of agricultural produce. A final assessment effort using all NCLAN data and including some farm program provisions in the analysis gave results similar to the first assessment. The final results confirm that ozone causes a substantial economic cost to society. Increases in the yields of eight major crops associated with a 25-percent reduction in ozone would result in a $1.9 billion annual benefit, whereas a 40-percent reduction would result in a $2.8 billion annual benefit. In contrast, a 25-percent increase in ozone would cause an additional $2.1 billion annual loss in these same crops.

A summary of economic estimates currently available suggests that the current seasonal ozone concentrations are causing annual losses in crop productivity of more than $3 billion.

What Can Farmers Do?
Many times over the past 25 years, we have been asked to determine the cause of crop damage after plant pathologists and entomologists were unable to determine the cause. Often, we were able to determine that the probable cause was ozone. In all cases, the farmers would ask what they could do to help control or prevent the damage. This has been a most frustrating question for researchers as well as farmers. The truth is that we have no good answer for the farmer that can be put to use in a reasonable time or with a high expectation of success. We have three principal options:

- Management practices,
- The use of resistant cultivars, and
- Education.

There are no specific management practices that can be widely recommended for controlling ozone effects on any crop species. However, some practices may be used in some circumstances to reduce the effects of ozone on plants. In greenhouse operations, for example, withholding water or minimizing water use before and during periods of high ozone should reduce the plant’s sensitivity to ozone. Likewise, when irrigation applications in regular farming operations can be planned to avoid days when high ozone is predicted, there should be less damage from ozone. There are chemicals that give some protection of selected crops from ozone exposure. These have been
tested, but results to date are tentative and the chemicals are too costly for recommendations to be made. Beyond these, no specific practices can be recommended.

The use of resistant cultivars is the only acceptable tool for the farmer. We know that resistant germplasm is present in all major crops that have been tested. Likewise, there are a number of resistant cultivars on the market and in use. Most of these are being inadvertently used by farmers because other qualities of the cultivars are desirable. Currently however, there are no specific programs with a focus on breeding for ozone resistance. Such programs may or may not become viable depending on the success of current ozone control strategies. Farmers could request information on the likely susceptibility to ozone of crop cultivars that they plan to use.

Our primary recommendation to farmers is to become knowledgeable about the effects of ozone on crop production systems and to give some consideration to cultivar selection and management practices where they may be helpful. A knowledge of the symptoms associated with ozone on the crops of interest and how these translate to effects on yield can be used to help the farmers make management decisions. Those who keep up with EPA attempts to control ozone concentrations will have a better idea of the future importance of ozone in production management.

Alternative Fuel Sources

by John W. McClelland, Agricultural Economist, Office of Energy, USDA, Washington, DC

President Bush declared that “Every American expects and deserves to breathe clean air . . . .” Toward that end, agriculture has a crucial role to play. Farm products not only can substitute for fossil fuels, but are also renewable, and we do not have to depend on other countries for them. Agriculture also must adjust, along with other sectors of the U.S. economy, as the Nation moves closer to the goal of clean air.

Passage of the 1990 Clean Air Act Amendments marked the first major overhaul of the Nation’s clean air legislation in more than a decade. This legislation will have a significant impact on U.S. agriculture. Mandates for clean fuels and oxygenated fuels are likely to boost the demand for