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PROTECTING AGRICULTURAL CROPS FROM THE EFFECTS OF TROPOSPHERIC OZONE EXPOSURE: Reconciling Science and Standard Setting in the United States, Europe, and Asia

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■ **Abstract** Ozone (O_3) is well documented as the air pollutant most damaging to agricultural crops and other plants. Most crops in developed countries are grown in summer when O_3 concentrations are elevated and frequently are sufficiently high to reduce yields. This article examines the difficulties in scientifically determining the reduction in yield that results from the exposure of agricultural crops to surface O_3 and then transforming that knowledge into efficient and effective regulatory standards. The different approaches taken by the United States and Europe in addressing this issue as well as the few studies that have been conducted to date in developing countries are examined and summarized. Extensive research was conducted in the United States during the 1980s but has not been continued. During the 1990s, the European community forged ahead with scientific research and innovative proposals for air-quality standards. These efforts included the development of a "critical level" (CL) for O_3 based on a cumulative exposure above a cutoff concentration below which only an acceptable level of harm is incurred. Current research focuses on estimating O_3 dosage to plants and incorporating this metric into regulatory standards. The US regulatory community can learn from current European scientific research and regulatory strategies, which argue strongly for a separate secondary standard for O_3 to protect vegetation. Increasing impacts of O_3 on crops are likely in developing countries as they continue to industrialize and their emissions of air pollutants increase. More research is needed on surface O_3 concentrations in developing countries, on their projected increase, and on the sensitivity that crop cultivars used in developing countries have to O_3. The threat of reduced agricultural yields due to increasing O_3 concentrations may encourage developing countries to increase their energy efficiency and to use different energy sources. This could simultaneously achieve a local benefit through improved regional air quality and a global benefit through a reduction in the emission of greenhouse gases.

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1. INTRODUCTION

Tropospheric ozone (O_3) is a major component of smog. A scientific review by the US Environmental Protection Agency (EPA) of the effects of O_3 found that exposure to ambient O_3 levels is linked to such respiratory ailments as asthma, inflammation and premature aging of the lung, and to such chronic respiratory illnesses as emphysema and chronic bronchitis (1). Detrimental effects on vegetation include reduction in agricultural and commercial forest yields, reduced growth and increased plant susceptibility to disease, and potential long-term effects on forests and natural ecosystems (1). O_3 is also believed to contribute to building and material damage. Once thought to be primarily an urban problem, elevated O_3 concentrations are now recognized as extending far beyond city limits. Elevated concentrations in rural regions significantly affect crop yields, forest productivity, and natural ecosystems.

In international negotiations to limit the emission of CO_2 and other greenhouse gases, a key issue has been the meaningful participation of developing countries. Major developing countries such as China and India have indicated their reluctance to devote resources to limiting CO_2 emissions in the face of more pressing domestic concerns. Although CO_2 emissions do not have a direct negative effect on public health or agriculture, the detrimental effects of the emission of reactive air pollutants that contribute to the formation of O_3 and smog are more easily recognized. Most developing nations are facing increasingly severe urban and regional air pollution, with associated costs, detrimental effects on human health (2) and natural ecosystems, and, as is discussed in this article, decreases in agricultural yields. Although in the near future developing countries may be relatively unconcerned about climate change, their levels of urban and regional air pollution are increasing in severity and are demanding attention. Fossil-fuel combustion emits both carbon dioxide (CO_2), the primary greenhouse gas, and reactive air pollutants such as nitric oxides ($NO_x = NO + NO_2$), the primary precursors for O_3 production outside of urban areas. By choosing energy technologies wisely, these countries can simultaneously reduce their emissions of NO_x and CO_2. These choices may result in improvements both in public health and in future agricultural yields, as well as in a reduction in the rate of increase in CO_2 emissions. For countries that are concerned about providing enough food for their growing populations while remaining independent of foreign food imports, the reduction in agricultural yields in key staple crops due to air pollution may be an incentive to explore methods that reduce both local and regional air pollution and CO_2 emissions.

Attempts to control tropospheric O_3 concentrations in the United States have been motivated primarily by the need to protect human health. However, studies conducted in the early 1980s in the United States and during the 1990s in Europe and other countries—including Japan, Pakistan, and Mexico—have indicated that many agricultural crops are adversely affected by exposure to tropospheric O_3 concentrations elevated above natural background levels. Crop sensitivities vary both by crop species and by the type of strain within a species (cultivar), as well as being influenced by various meteorological factors, including temperature, humidity, soil moisture, and radiation. However, the yield of several major food crops appears to decline when exposed to O_3 concentrations, which have become common during the growing season in the United States and Europe. Research indicates that exposure to O_3, alone or in combination with other pollutants, results in approximately 90% of the air-pollution–induced crop loss in the United States (3).

The standard that best protects human health is different from the one needed to protect crops. As is shown in this article, setting the same standard to protect both human health and welfare is not optimal for either evaluating damage to vegetation or protecting it. A variety of exposure indices have been developed to evaluate crop-yield loss based on experimental data. Those indices that accumulate O_3 concentrations above a threshold over the growing season better represent crop loss than indices that rely on either seasonal mean or peak O_3 concentrations. Recent research in Europe has emphasized the development of standards that account for the variability of flux into the plant rather than just ambient O_3 concentration or cumulative exposure.

This article focuses on research that has been conducted on the exposure of agricultural crops to enhanced concentrations of surface O_3, the reductions in crop yields that result, the development of environmental standards to protect vegetation from O_3 damage, and the costs associated with lost yields. This paper is divided into seven sections. Section 2 is an overview of the science of tropospheric O_3 formation, trends in surface O_3 concentration, and the mechanism by which O_3 damages plant tissue. Section 3 reviews the regulatory policies and crop-loss assessment studies conducted to date in developed (United States, Europe, and Japan) and developing countries and presents these results in tabular form. Section 4 summarizes the strengths and weaknesses of different exposure indices. Section 5 is an overview of the economic assessments of the costs associated with lost yields. Section 6 makes recommendations for future research, and Section 7 concludes with recommendations for the form of an appropriate standard to protect vegetation from O_3 exposure.

2. BACKGROUND SCIENCE

2.1. Chemistry of Tropospheric O_3 Formation

O_3 is a pollutant that is formed in the troposphere from a complex series of sunlight-driven reactions between nitrogen oxides ($NO_x = NO + NO_2$), carbon monoxide (CO), and hydrocarbons, and it is also transported into the troposphere from the stratosphere. The primary source of NO_x to the troposphere is fossil-fuel combustion. Secondary sources of NO_x include biomass burning, lightning, and soils (4). Hydrocarbons are emitted from a range of human activities, including fossil-fuel combustion, direct evaporation of fuel, solvent use, and chemical manufacturing. Terrestrial vegetation also provides a large natural source of hydrocarbons. NO_x and CO are both directly harmful to human health and are regulated as criteria pollutants by the US EPA.

O_3 production occurs via the catalytic reactions of NO_x with CO and hydrocarbons in the presence of sunlight. O_3 production is favored during periods of high temperature and insolation, which typically occur under stagnant high-pressure systems in summer. A schematic representation of O_3 formation is shown in Figure 1. A critical difficulty in regulating O_3 has occurred because in regions of high NO_x (primarily urban centers and power plant plumes), O_3 formation is limited by the availability of hydrocarbons. In regions of low NO_x (primarily rural areas with abundant emission of natural hydrocarbons), O_3 formation is limited by the availability of NO_x (5). Figure 2 shows O_3 concentrations as a highly nonlinear function of volatile organic compounds (VOC) and NO_x emissions (6). Scientists and regulators now recognize that to control O_3 concentrations in most nonurban locations, because of the availability of natural hydrocarbons, it is necessary to limit the emission of NO_x.

2.2. Trends in Surface O_3 Concentrations

O_3 concentrations vary considerably from day to day, year to year, and location to location because of meteorological conditions (winds, sunlight, temperature, humidity) that vary in both time and space and because of variations in the emission of NO_x and hydrocarbons. Thus, establishing regional trends must be done in the face of significant variability. A clear upward trend in surface O_3 concentrations from preindustrial times to the mid-1980s has been established, however.

Concentrations of surface O_3 in central Europe 100 years ago were approximately 10 parts per billion (ppb) and exhibited a seasonal cycle with a maximum during the spring months (8). By 1950, O_3 levels at a rural site near Paris were

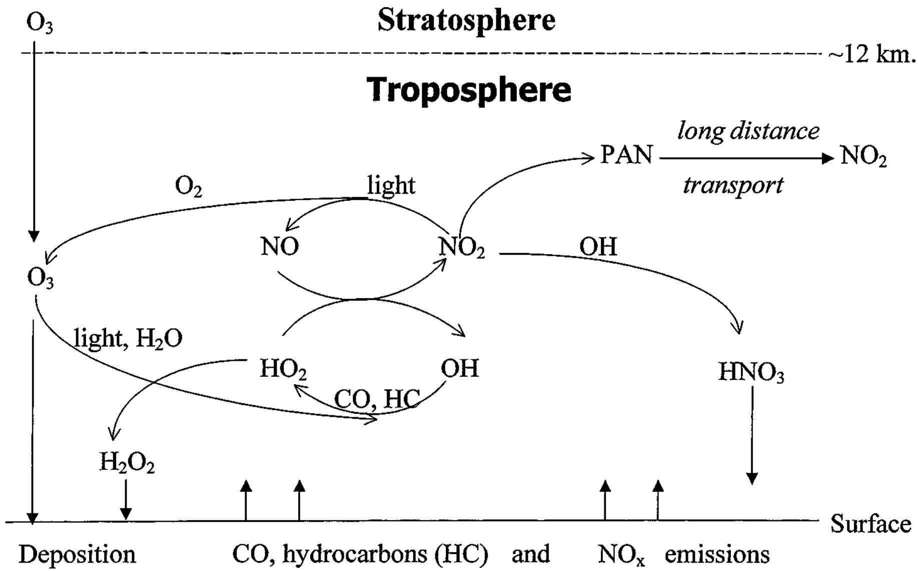

Figure 1 Schematic of tropospheric O_3 production. O_3 is both transported into the troposphere from the stratosphere and produced within the troposphere by photochemical reactions between NO_x ($NO_x = NO + NO_2$) and HO_x ($HO_x = OH + HO_2$). Emissions of NO_x, CO, and hydrocarbons from fossil-fuel combustion, fires, and biogenic processes lead to the production of O_3 via a complex set of catalytic chemical reactions that take place in the presence of sunlight. NO_x is primarily removed from the atmosphere via conversion to nitric acid (HNO_3), which is deposited at the earth's surface. HO_x, produced by the oxidation of CO and hydrocarbons, is removed by conversion to peroxides (H_2O_2), which are also deposited at the earth's surface. Peroxyacetylnitrate (PAN) is a reservoir species for NO_x that is stable at low temperatures and decomposes at warm temperatures, hence permitting long-distance transport of NO_x, the key precursor to O_3 formation in rural locations.

about 15–20 ppb and around 1980 were 30 ppb (9). Trends of rural O_3 in Europe in the 1980s have been statistically insignificant (9). Like Europe, the United States has had no significant increasing trend in O_3 concentrations detected in rural data between 1980–1995 (10). However, median rural O_3 concentrations in the eastern United States on summer afternoons during this period ranged from 50–80 ppb with ninetieth percentile values frequently in excess of 100 ppb (10). These levels are known to cause crop damage. Maximum O_3 concentrations are no longer observed in the spring but occur in summer because of increased photochemical production of O_3 resulting from increased emissions of NO_x and VOCs. Most crops in the world are grown in summer when O_3 photochemical production and resulting concentrations are at their most elevated and are frequently sufficient to reduce crop yields.

In developing countries there is little data available on the ambient concentrations of O_3 in rural areas. However, the current increase in fossil-fuel combustion and resulting NO_x emissions are projected to result in increasing O_3

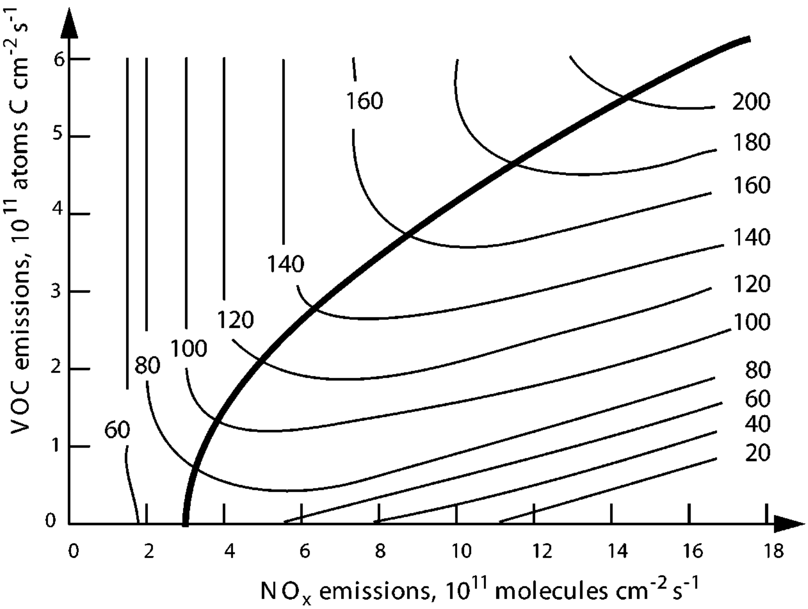

Figure 2 NO_x versus hydrocarbon limitation of O_3 production. O_3 concentrations (in parts per billion by volume, ppbv) are calculated by a model as a function of NO_x and hydrocarbon (VOC) emissions. The thick line separates the NO_x-limited (*top left*) from the hydrocarbon-limited (*bottom right*) regimes. Note that in a NO_x-limited regime, O_3 concentrations increase as NO_x emissions increase but do not change as hydrocarbon emissions increase. In a hydrocarbon-limited regime, O_3 concentrations increase more quickly with an increase in hydrocarbon emissions and more slowly with an increase in NO_x emissions (6). Immediately surrounding the line, increases in either NO_x or hydrocarbon emissions will result in an increase in O_3 concentrations. [Adapted from Jacob (7).]

concentrations. For example, in China, NO_x emissions are projected to triple between 1990 and 2020 (11).

Tropospheric O_3 concentrations elevated above natural background levels were initially identified in urban areas. Today it is recognized that O_3 is a regional rather than an urban pollution problem, and concerns about international transboundary and intercontinental transport are increasing. In fact, because of the nonlinear NO_x/hydrocarbon chemistry, O_3 concentrations are frequently higher downwind of cities than they are in the heart of an urban center, making them a particular problem for agricultural production. The increasing dependence that industrialized society has placed on fossil fuels has resulted in increasing emissions of O_3 precursors and pollution in "metro-agro-plexe" regions in which intense urban-industrial and agricultural activities cluster together in a single large network of lands affected by human activity (12).

2.3. Mechanisms by Which O_3 Damages Plant Tissue

Uptake of O_3 by plants is a complex process involving micrometeorology that brings O_3 into the plant canopy. Once in the canopy, O_3 can be absorbed by surfaces (stems, leaves, and soil) and into tissues, primarily into leaves via the stomata (small openings in the bottom of the leaf surface whose aperture can be controlled by the plant). In general, stomata open in response to light and increasing temperature and close in response to decreasing humidity, water stress, and increased CO_2 or air pollutants, such as O_3 (1, 13). To modify or degrade cellular function, O_3 must diffuse in the gas phase from the atmosphere surrounding the leaves, through the stomata, become dissolved in water coating the cell walls, and then enter the cells of the leaf (1). Uptake of O_3 by leaves is controlled primarily by stomatal conductance, which varies as a function of stomatal aperture. Uptake of O_3 by plant cuticles was found to be a negligible fraction of uptake by plants with open stomata (14). There is a general pattern of stomatal opening in the morning due to the presence of sunlight and a closing in the evening, with possible midday stomatal closure occurring during periods of high temperature and drought (15). Absorption of O_3 by leaves is a function of both stomatal conductance and ambient O_3 concentrations. O_3 absorption can be estimated from models of stomatal conductance and O_3 concentrations.

Plants are able to protect themselves from permanent injury due to O_3 exposure either through thick cuticles, the closure of stomata, or detoxification of O_3 near or within sensitive tissue. These protection devices come at a cost: either a reduction in photosynthesis, in the case of stomatal closure, or in carbohydrate used to produce detoxification systems (1, 16). For detoxification to occur, it appears that the plant produces an antioxidant that reacts with O_3, thus protecting the tissue from damage (17). O_3 that has not been destroyed reacts at the biochemical level to impair the functioning of various cellular processes (18). Black et al. (19) reviews several studies that demonstrate direct effects of O_3 on various reproductive processes, including pollen germination and tube growth, fertilization, and the abscission or abortion of flowers, pods, and individual ovules or seeds (19). Physiological effects of O_3 uptake are manifest by (*a*) reduced net photosynthesis, (*b*) increased senescence, and (*c*) damage to reproductive processes (1, 19). Thus O_3 exposure will have an impact on both plant growth and crop yields. The exact response of a given specimen will depend on its ability to compensate for O_3 injury. Dose-response relationships thus vary by plant species, crop cultivar, developmental stage, and external environmental factors, such as water availability and temperature, which influence the opening and closing of stomata.

Because of the expense involved in conducting long-term growth studies to determine O_3 effects on plants, only a small proportion of the total number of commercial crop cultivars have been examined. However, an enormous variability in O_3 sensitivity has been found. Currently, standards to protect crops from exposure to O_3 do not account for the physiological aspects of the effects O_3 has on plants but rather are based on either peak O_3 concentrations (United States) or cumulative exposure to O_3 (Europe). Recent research has focused on establishing the parameters that control the intake of O_3 into plants so as to develop a standard that is physiologically based rather than an empirical fit to data collected in exposure-response experiments.

3. REVIEW OF CROP-LOSS ASSESSMENT STUDIES AND REGULATORY POLICIES

An evaluation of the impacts of O_3 on crop yields on a local, regional, or national scale requires three types of information: (*a*) knowledge of crop distributions and yields within the region under study; (*b*) an air-quality database outside of urban areas from which estimates of crop exposure to O_3 can be made; and (*c*) an air-pollutant–dose/crop-response function that relates crop yield of specific cultivars to O_3 exposure (21). In most countries, crop distributions and yields are the best known of the three needed parameters. In the United States and Europe, O_3 monitoring networks exist; however, almost no ambient O_3 data exists outside of urban areas in developing countries. Large-scale studies (described below) have been conducted in the United States and Europe to establish O_3-exposure/crop-response relationships for crop cultivars grown in these regions. Tables 1 and 2 provide an overview of the experimental studies conducted in the past decade on yield response to O_3 exposure as an extension of the review conducted by Heck (22).

3.1. United States

In the United States, the Clean Air Act mandates the protection of human health and welfare from the effects of exposure to tropospheric O_3 through the setting of primary and secondary National Ambient Air Quality Standards (NAAQS). Public health is protected by primary standards. Ecological resources, including crops, are part of public welfare and are protected by secondary standards. In the United States to date, the primary and secondary standards for O_3 have been set equal to each other. In 1997, a new EPA regulation that increased the stringency of both the primary and secondary O_3 standards from 0.12 parts per million (ppm) of O_3 measured over 1 hour, not to be exceeded more than three times in 3 years, to 0.08 ppm measured over 8 hours, with the average fourth highest concentration over a 3-year period determining whether a location is out of compliance. This standard was contested in court, and in February 2001, the US Supreme Court upheld the way the federal government sets clean-air standards. The NAAQS are required to be reviewed every five years and were last reviewed in 1996 (1). Hence, with the upcoming review, the US EPA has the opportunity to consider a secondary standard specifically designed to protect vegetation.

A recent analysis of O_3 data for the contiguous United States for the 1980–1998 period shows that the average number of summer days per year in which O_3 concentrations exceeded 0.08 ppm is in the range of 8–24 in the northeast and Texas and 12–73 in Southern California (23). The probability of violation increases with temperature and exceeds 20% in the northeast for daily maximum temperatures above 305 K (23). It appears that violations are considerably more widespread for the new standard than for the old standard. The pollution-control policies enacted to bring areas into compliance with the old standard have been at least as effective in lowering daily maximum 8-hour average O_3 concentrations as they have been in lowering daily maximum 1-hour average O_3 concentrations (23).

In 1979, during a review of the NAAQS for O_3, the US EPA recognized the importance of determining O_3-dose/plant-response relationships for economically important crop species. They chose to use crop yield as the metric of response because of its usefulness in setting a secondary standard to protect public welfare (21). As a result, in 1980, the EPA initiated the National Crop Loss Assessment Network (NCLAN), which was the first large-scale and systematic study of the impact of O_3 on crops in the world.

The primary objectives of the NCLAN study were to (*a*) define the O_3 exposure/crop-yield response relationship for the major agricultural crops; (*b*) assess the national economic consequences resulting from the reduction in agricultural yield; and (*c*) increase understanding of the cause/effect relationship that determines crop response to pollutant exposure (21). At the start of the NCLAN study, Heck et al. estimated that yield losses due to O_3 exposure accounted for 2%–4% of the total US crop production (3). The NCLAN study findings are reviewed by Heck (22). Table 1 includes a summary of smaller studies conducted in the United States following NCLAN and their findings. These studies corroborate variable yet substantial reductions in yield in a variety of crops as a result of elevated O_3 concentrations. For example, a 40% reduction in soybean yield was found for soybeans exposed to 70–90 ppb of O_3, but no effect was seen on broccoli at 63 ppb of O_3.

The NCLAN program utilized monitoring of ambient O_3 concentrations by an extensive national network operated by the EPA as part of the Storage and Retrieval of Aerometric Data system. A statistical process, called kriging, was used to interpolate the O_3 concentrations observed at the monitoring stations to the ambient 7-h mean O_3 concentrations at the field sites during the 5-month growing season (May-September) (24).

During the NCLAN program, plants were grown in the field using open-top chambers in which the O_3 concentration to which the plants were exposed could be controlled and monitored. Early in the program, O_3 was added in fixed increments to the chambers for 7 h/day in excess of the ambient O_3 concentrations. Later the program was revised so that O_3 was added for 12 h/day.

Heck et al. (25) compared four O_3 averaging times for their efficacy in fitting the O_3-dose/crop-yield–response data. Two seasonal means [1-h/day and 7-h/day (0900–1600 h) mean O_3 concentrations], and two peak concentrations (maximum daily 1-h and 7-h mean O_3 concentrations occurring during the growing season) were used. Only the seasonal mean O_3 statistics were found to be useful for estimating yield reductions of a given crop from data obtained from different sites or different years, whereas peak statistics could not be used for other locations or

TABLE 1 Field experiments on O_3 impacts on agricultural crops in developed countries[a]

Location	Crop	Method	Response	Reference
US—Southern California	Broccoli (*Brassica oleracea L.*), lettuce (*Lacuca dativa L.*), and onion (*Allium cepa L.*)	OTC with CF (M12 = 14 ppb), NF (36 ppb), and 1.5 times NF (63 ppb); exposed from 4 weeks after germination till harvest	Yields of lettuce and broccoli were not affected by O_3+; only one cultivar of onions had 5% yield loss at AA	62
US—Maryland	Soybean (*Glycine max* L. Merr. cv. Clark)	OTC with CF (M7 = 23 ppb), NF (40 ppb) and O_3++ (66 ppb)	Yield reduced by 15% in NF, and 26% in O_3++ relative to CF	63
US—San Joaquin Valley, CA	Cotton (*Gossypium hirsutum* L. cv. SJ2)	OTC with CF (M7 = 7–19 ppb) and NF (23–53 ppb), and AA (31–56 ppb) in open plots	Yield losses ranged from 0% to 20% in NF compared with CF across all experimental sites and years and in proportion to O_3 concentrations	64
US—North Carolina	Tomato (*Lycopersicon esculentum L.* cv. Tiny Tim)	CSTR chambers with 0 ppb O_3 and O_3^{++}(daily mean = 80 pph)	Final yield reduced by 31% at O_3++	65
US—Raleigh, NC	Soybean (*Glycine max* L. Merr. cv. Essex)	OTC with CF (M12 = 21–25 ppb) and O_3++ of 70–92 ppb	Seed yield reduced by 41% at O_3++ relative to CF	66
UK—Northumberland	Winter wheat (*Triticum aestivum* L. cv. Riband), winter oilseed rape (*Brassica napus* ssp. *Oleifera* var. *biennis* L.), five cultivars	Simple unclosed fumigation system with treatments of AA with daily mean of 30 ppb and O_3++ at 80 ppb	13% yield reduction of winter wheat and 14% yield reduction of winter oilseed rape at O_3++ relative to AA	67, 68
Europe (ESPACE-wheat sites)	Spring wheat (*Triticum aestivum* L. cv. Minaret)	OTC with NF (M12 = 17–44 ppb) and O_3++ (32–73 ppb)	O_3++ did not cause significant yield reduction for Minaret relative to NF	48, 69, 70
Netherlands	Bean (*Phaseolus vulgaris* cv. Lit)	Use of EDU	Use of EDU enhanced dry pod yield by 20% on average	71
Netherlands	Bean (*Phaseolus vulgaris* cv. Pros)	OTC with various treatments (M9 = 0–75 ppb or AOT 40 = 0–17700 ppbh)	Yield loss is linearly related to AOT40; 5% yield loss corresponds to AOT40 of 1600 ppbh, and 10% loss to 1700 ppbh	72

UK—Sutton Bonington	Potato (*Solanum tuverosum* cv. Bintje)	OTC with AA (M8 = 21 ppb) and O_3++ (50 ppb)	O_3++ did not affect tuber yields but reduced above-ground dry weight by 8.4% compared with AA	73
UK—Sutton Bonington; France—Pau	Bean (*Phaseolus vulgaris* cv. Lit)	OTC with CF (M7 = 8 ppb), NF, or O_3++	10% yield reduction in England at 38 ppb, and 11% in France at 39 ppb, compared with CF	74
Italy—central	Peach tree (*Prunus persica* L. cv. Batsch)	OTC with CF (AOT60 = 4 ppbh), AA (5398 ppbh), and O_3++	No significant impact on fruit yield at AA compared with CF, but negative impact on plant growth and fruit quality found	75
Italy—north	Bean (*Phaseolus vulgaris* cv. Taylor's horticulture)	OTC with CF (7-h daily mean = 10 ppb) and NF (45–50 ppb)	18%–31% seed yield loss in NF relative to CF	76
Sweden—southwest	Spring barley (*Hordeum vulgare* L. cv. Lina)	OTC with CF (M7 = 6 ppb), NF (29ppb), or NF with O_3++ (45 ppb)	No yield reduction at up to 45 ppb of M7 compared with CF	77
Spain—eastern	Watermelon [*Citrullus lanatus* (Thunb.) Matsum & Nakai cv. Toro]	OTC with CF (10-h daily mean = 8 = 11 ppb in 1988 and 8–14 in 1989) and NF (21–45 ppb in 1988 and 36–61 ppb in 1989)	Fruit yield loss was 19% in 1988 and 39% in 1989	78, 79
Japan	Rice (*Oryza sativa* L. cvs. Koshi-hikari and Nippon-bare)	Field chamber system with O_3 concentration at 0.5, 1.0, 1.5, 2.0, or 2.75 times AA (i.e. M7 = 15–97 ppb)	Yield loss at 50 ppb ranges from 3% to 10% relative to background level of 20 ppb; results comparable to rice studies in the US (81)	80

[a]AA, ambient air; AOT40 (AOT60), accumulated exposure of hourly concentrations (for daylight hours during which the mean global radiation was 50 W/m^2 or higher) above 40 (60) ppb over the growing season; CF, charcoal-filtered air; CSTR, continuously stirred tank reactor; EDU, N-(2-(2-oxo-1-imidazolidinyl) ethyl)-N′phenylurea, an antioxidant; ESPACE-wheat, European Stress Physiology and Climate Experiment Project 1, on wheat; M7, seasonal mean of all hours from 0900 to 1600 h; M12, seasonal mean of all hours from 0800 to 2000 h; NF, nonfiltered air where O_3 concentration in the OTC is near ambient level; OTC, open-top chambers; O_3+, O_3 concentrations above the CF levels; O_3++, O_3 concentrations above the AA levels.

time periods (25). A study evaluating 613 numerical exposure-response indices found that indices that weight peak concentrations using a sigmoid (or discrete 0-1) weighting scheme and accumulate exceedances over a threshold concentration of 60 ppb give a better fit to yield data in the United States than do indices that use mean concentrations over a growing season or peak values alone (26, 27). Also, preferential weight given to O_3 concentrations during the daytime (0800–2000 h), when leaf stomata are open and gas exchange is maximized, was found to be important (28). In addition, indices that positively weighted O_3 exposure between plant flowering and maturity resulted in additional improvement but were deemed too complex to be used in an air-quality standard.

The indices described above are empirical and do not directly account for the physiological mechanism by which O_3 doses are delivered or physiological effects incurred. More recent work has begun to examine the physiological mechanisms by which plants are affected by O_3 and to propose standards that take O_3 flux as it relates to plant response into account. An air-quality standard to protect vegetation that is biologically relevant, and hence includes factors that influence flux (concentration and conductance) and effective absorbed dose (rate of uptake minus rate of defensive neutralization or repair), has been advocated recently in the United States (29) because damage to vegetation is more likely correlated with a dose-based index than an exposure-based index. Research is needed to refine various techniques for determining fluxes into plants and for accumulation of flux data in the standard setting process. Further research is also needed on plant defensive responses, canopy-scale conductances, and plant response, including effects on photosynthesis (29). As is discussed in the next section, some of this research is under way in Europe.

As part of the standard setting process, EPA reviews all pertinent literature every 5 years (most recently in 1996) and publishes a summary in the *Air Quality Criteria for Ozone and Related Photochemical Oxidants* document (1). An index that accumulates all hourly O_3 concentrations during the growing season and gives greater weight to higher concentrations has major advantages over mean and peak indices, as judged by better statistical fits to the data (30). Unfortunately, to date, the scientific findings reviewed in the EPA's criteria document have not been sufficiently influential to result in setting a secondary standard that is more protective of crops and natural vegetation than the primary, peak-concentration–based standard used today.

3.2. Europe

Although European research on the impact of O_3 on crops started later than research in the United States, it forged ahead during the 1990s and has been more influential in the standard-setting process than it has been in the United States. The European approach has centered around the concept of a "critical level" (CL), which is based on a cumulative exposure above a cutoff concentration below which only an acceptable level of harm is incurred.

During the late 1980s and 1990s, the potential impact of ground-level O_3 on plants and human health came into focus in Europe. Between 1987 and 1991 the basic NCLAN methodology was used in nine countries in Europe on a variety of crops, including wheat, barley, beans, and pasture, during the European Open Top Chamber (EOTC) program. Like the NCLAN studies, the experiments involved the exposure of a number of crops grown in open-top containers to a range of O_3 concentrations over the growing season. Experimental results indicated yield reductions were highly correlated with cumulative exposure to O_3 above a threshold of 30–40 ppb during daylight hours (31). A cumulative indicator of O_3 exposure above a 40-ppb threshold (AOT40) was therefore established (for a full description of this standard, see Section 4).

The AOT40 associated with a 5% yield reduction of wheat was determined to be the most appropriate value for a CL for O_3 (32). Based on this criteria, the AOT40 was set at 3000 ppbh accumulated during daylight hours for the three months (May, June, and July) when clear sky radiation is above 50 W/m2 (32–34). This is the time period during which spring planted crops experience maximum growth and are therefore likely most sensitive to O_3. Wheat was selected for the derivation of the CL because available data was more comprehensive and because the crop appeared to be relatively sensitive to O_3. However, it is known that there are large variations in response to O_3 between species and that environmental conditions alter plant uptake and response (32). Currently, the AOT40 parameter exceeds 3000 ppbh in most of the European Union with the exception of northern Scandinavia and the UK (32a). This implies that most of Europe could be losing at least 5% of its annual wheat yield.

The AOT40 concept forms the basis of the “level 1” analysis of the potential risk of O_3 on plants in Europe. The level 1 approach does not consider biological or climatic factors that will influence the O_3 dose and vegetative response. To accurately estimate the yield loss caused by O_3, it is believed that a “level 2” approach is needed. An exceedance of the current level 1 CL does not necessarily mean that there will be damage to vegetation, but only that the risk of damage exists for sensitive species and conditions. Likewise, the degree to which the level 1 standard is exceeded is insufficient to determine the extent of damage to vegetation or the economic impact of O_3 damage. This is because exposure to high O_3 levels is correlated with high temperatures and humidity. During hot, dry conditions, plants usually close their stomata, which helps protect them from O_3 exposure. Also, plant sensitivity varies as a function of plant growth stage at the time of the excess O_3. The level 2 approach would include consideration of parameters that influence the flux of O_3 into the plant and which are critical in converting O_3 exposure to O_3 dose (35). Parameters important in determining O_3 dose include soil moisture conditions, vapor pressure deficit (VPD), and temperature.

A recent study on wheat in Sweden found that when AOT40 is compared with an alternative flux-based standard (CFO_3), which in addition to O_3 concentration accounts for VPD, light, and temperature, CFO_3 provided a more consistent relationship between relative yield loss and O_3 exposure than did AOT40 (36). CFO_3 is the cumulative flux of O_3 (uptake) to the leaves. In northern Europe, although the O_3 concentrations are lower than in southern and central Europe, the potential for O_3 uptake at a given O_3 concentration is higher because of higher levels of humidity (36). Thus, the net O_3 uptake may vary according to a different geographical pattern than indicated by AOT40. A standard that was able to weight O_3 concentration based on environmental factors of importance in O_3 uptake would be an improvement over the current methods of evaluating damaging O_3 concentrations.

Recent findings by the UN/ECE ICP–Vegetation Program (the United Nations Economic Commission for Europe International Cooperative Program on effects of air pollution and other stresses on crops and nonwood plants) further the objective of implementing a level 2 standard. The UN/ECE ICP–Vegetation Program coordinates ambient air experiments over large areas of Europe to investigate the effects of ambient O_3 pollution on crops. In 1995 and 1996, O_3 injury was observed at sites throughout Europe from the United Kingdom to Russia and from Sweden to Italy (37). Based on the 1995 data, two short-term CLs that incorporate O_3 dose and air-saturation VPD were derived. They are (*a*) an AOT40 of 200 ppbh over 5 days when mean VPD (0930–1630 h) is below 1.5 kPa and (*b*) and AOT40 of 500 ppbh over 5 days when mean VPD (0930–1630 h) is above 1.5 kPa (37). Thus the ICP vegetation experiments have shown that O_3 injury can occur over much of Europe and that plants are most at risk in conditions of high atmospheric humidity. The AOT40 CLs, modified to include VPD criteria, are a first step toward identifying a feasible standard that takes flux, and hence O_3 dose to the plant, into account.

The implementation of an effects-based international or national control strategy aimed at reducing the impacts of O_3 on vegetation and associated air pollutants requires an integrated approach. The UK Photochemical Oxidant Review Group concluded that all the following are needed: (*a*) a definition of the appropriate CLs; (*b*) maps showing geographically resolved CLs, assigned on the basis of specific vegetation types, (map 1); (*c*) maps showing geographically resolved O_3 exposures (map 2); (*d*) maps based on overlays of maps 1 and 2 showing geographically where and to what extent CLs are exceeded; (*e*) maps based on current or future emission scenarios showing modeled O_3 exposures (map 3); and (*f*) maps based on overlays of maps 1 and 3 showing where O_3 CLs are predicted to be exceeded in the future (32). In addition, maps of such key climatological parameters as temperature and humidity are necessary to improve the CL concept so that it becomes a measure of plant dose rather than exposure. Thus, a truly interdisciplinary approach is needed, with a dialog between members of the effects, measurement, mapping, modeling, and policy-making communities. Such efforts are under way in Europe.

The European Long Range Transboundary Air Pollution Convention (LRTAP) was the first internationally legally binding instrument to deal with problems of reactive air pollution on a broad regional basis. It was signed in 1979 and entered into force in 1983. It has greatly contributed to the development of international environmental law and created the essential framework for controlling and reducing the damage that transboundary air pollution can cause to human health and the environment in Europe. LRTAP was initially written to control the emission of sulfur dioxide (SO_2) emissions. A number of protocols followed ratification of the Convention, including the 1988 Protocol on the Control of Emissions of Nitrogen Oxides (NO_x) and their Transboundary Fluxes, and the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone (38). The NO_x protocol initially required the freezing of emissions of nitrogen oxides at 1987 levels. This was a crucial first step to controlling O_3 concentrations in Europe. The 1999 Gothenburg Protocol sets emission ceilings for 2010 for four pollutants: sulfur, NO_x, volatile organic compounds (VOCs), and ammonia. These ceilings were negotiated on the basis of scientific assessments of pollution effects and abatement options. Parties whose emissions have more severe environmental or health impacts and whose emissions are relatively cheap to reduce will have to make the biggest cuts. Once the Gothenburg Protocol is fully implemented, Europe's NO_x emissions will be cut by 41% and its VOC emissions by 40%, compared with 1990. In addition, the European Union is involved in negotiations that are likely to reduce NO_x emissions below levels agreed on in LRTAP (M. Amman, personal communication). These substantial reductions in emissions should help to reduce O_3 levels in Europe and will likely bring much of Europe closer to the current growing-season level 1 AOT40 CL of 3000 ppbh O_3. Further research is needed to determine whether these reductions in NO_x emissions will be sufficient to bring O_3 below the level 2 standards that are currently beginning to be considered.

3.3. Asia

Although O_3 is the most important air pollutant affecting crop production in North America and Europe, its impact in developing countries, where the economic and social consequences of loss of production may be critical, is uncertain. A recent review by Ashmore & Marshall (39) assesses the current and future significance of O_3 impacts on agriculture in Asia, Africa, and Latin America (39). Outside of global chemical tracer model results, little information is available on O_3 concentrations in rural parts of these continents, but because of expectations of increased emissions of O_3 precursors, it is likely that O_3 concentrations will become sufficiently high in the future to have increasingly adverse effects on sensitive species (39).

As emissions from fossil-fuel combustion have increased in Asia, Japanese scientists have become interested in the impact of O_3 and SO_2 deposition on agriculture and forest ecosystems. Some small studies have been conducted in India and Pakistan, and a study conducted in the United Kingdom simulated Chinese agriculture. Studies conducted on the adverse effects of O_3 on crops in developed countries (including Japan) are listed in Table 1. Table 2 summarizes the studies conducted in developing countries to date. The rice cultivars used in a Pakistani study appear to have a much greater sensitivity to O_3 than other cultivars (40). Similar variability among cultivars of other crops is possible, making it clear that further studies of cultivars used in developing countries are critical. It is possible that given local O_3 concentrations and crop strains used in developing countries,

TABLE 2 Field experiments on O_3 effects on agricultural crops in developing countries[a]

Location	Crop	Method	Response	Reference
Pakistan—Punjab	Winter wheat (*Triticum aestivum* cvs. Pak-81 and Chakwal-86) Rice (*Oryza sativa* cvs. Basmati-385 and IRRI-6)	OTC with CF (6-h daily mean = 5 ppb) and NF (25–45 ppb for wheat and 10–54 ppb for rice)	33%–47% yield reduction in wheat and 37%–51% in rice in NF, compared with CF	82–84
Indian—Punjab	Potato (*Solanum tuberosum* cv. Kufri jyoti)	Dusting with activated charcoal or addition of EDU	Plants treated with EDU did not develop visible injury, whereas untreated plants did	85
Egypt—Abbis and Alexandria	Radish (*Raphanus sativus*), turnip (*Brassica rapa*)	Application of EDU	In radishes, root and shoot dry weight decreased, respectively, by 30% and 17% in Abbis and 24% and 18% in Alexandria; in turnip, they decreased by 17% and 11% in Abbis and showed no significant effect in Alexandria	86
Mexico—Montecillos	Bean (*Phaseolus vulgaris* cvs. Canario 107 and Pinto III)	Application of EDU	4.5% yield reduction in untreated plants of Canario 107; 40.7% yield reduction in untreated plants of Pinto III	39
China—Chongqing	11 local crop species: eggplant, cauliflower, Chinese leaves, tomato, lettuce, wheat, maize, radish, zucchini, pepper, rice	Seed sown in controlled chambers at Newcastle University, UK; OTC with CF and air with O_3 concentration and pattern similar to Chongqing (hourly mean of 15–75 ppb; 7-h daily mean = 59 ppb) over a 28-day period	Typical foliar injury restricted to rice, eggplant, tomato, and pepper; all species but wheat, maize, radish, and zucchini found to be O_3 sensitive in terms of growth; only eggplant and pepper (cv. Yu2) showed significant O_3-induced reductions in root-shoot partitioning; rice appeared to be more sensitive in terms of growth and visible injury than cultivars grown in Pakistan, Japan, and US	87

[a]CO_2+, enhanced CO_2 concentration above ambient levels. Other abbreviations as in Table 1.

O_3 may cause a larger reduction in crop yield in developing than in developed countries. No Asian or developing country government has organized a large-scale investigation of the effect of O_3 on crops, such as has been conducted in the United States and Europe. Investigations have partly made use of the experimental results of the US NCLAN study for modeling work or have examined specific crop cultivars to establish a dose-response relationship for a local crop strain. Recent work in Japan has attempted to improve and generalize the dose-response functions obtained by the NCLAN experimental results by utilizing crop-growth models (41). These models attempt to parameterize physiological functions at the individual plant and leaf level in order to explain the variation in O_3-dose/yield-reduction–response relationships. There is, however, an increasing interest in better understanding the impacts of O_3 on agriculture in Asia.

A recent study on the impacts of O_3 on agriculture in China utilized a global three-dimensional chemical tracer model to calculate surface O_3 concentrations and then applied the NCLAN and EOTC studies dose-response data to Chinese crops. It found that reductions in crop yields in 1990 in China were less than 3% for most grain crops (except soybean) but that predictions for 2020 suggested that crop losses for soybeans and spring wheat might reach 20% and 30%, respectively (42). Another study that made measurements of O_3 concentrations at four locations in China and then used a regional model to predict O_3 concentrations over the rest of the country also concluded that impacts on Chinese wheat were likely to become significant in the future (43). China's concerns about food security may make greenhouse gas mitigation strategies that reduce surface O_3 concentrations more attractive than those that do not. Three-dimensional photochemical modeling indicates that the outflow of emissions from China results in increases in O_3 concentrations in the boundary layer (0–2.1 km) over Japan (44). It is expected that as fossil-fuel combustion increases in China, the outflow from continental Asia will have an increasingly large effect on O_3 concentrations above Japan and the Pacific Ocean, and potentially the United States as well (45, 46).

4. SYNERGISTIC EFFECTS OF O_3 AND OTHER ENVIRONMENTAL FACTORS ON CROPS

A crop-loss assessment effort must understand the interrelationship between O_3, other air pollutants, and biological and environmental factors (22). Heck (22) reviews observed interactive effects. Table 3 summarizes similar studies that were carried out during the 1990s, as an update of Heck (22). Most of this research was conducted as individual studies, except for the European Stress Physiology and Climate Experiment Project 1, on wheat (ESPACE-wheat). The ESPACE-wheat project was initiated in 1994 to investigate the response of agroecosystems to elevated atmospheric carbon dioxide concentrations, climatic variation, and physiological stresses (such as O_3 or water/nutrient shortage). From 1994–1996, a total of 25 open-top chambers experiments were carried out in nine European countries, and a large database was created to provide data to improve, extend, and validate mechanistic wheat-growth simulation models (47). The program employed a

TABLE 3 Field experiments on the interactive effects of O_3 and other environmental factors on crops

Location	Crop	Effect	Reference
O_3 and CO_2			
US—North Carolina	Tomato (*Lycopersicon esculentum L.* cv. Tiny Tim)	CO_2+ significantly enhanced growth and yield whereas O_3+ suppressed vegetative growth and reduced fruit yield; CO_2+ ameliorated some of the detrimental effects of O_3+ on vegetative growth and yield of mature fruit	65
US—North Carolina	Soybean (*Glycine max* L. Merr. cv. Essex)	O_3+ (CO_2) stressed plants and suppressed (increased) growth and yield; CO_2-induced stimulation was greater for plants stressed by O_3+ than for nonstressed plants	88–90
US—Massachusetts	Soybean (*Glycine max* L. Merr. cv. Essex)	O_3+ reduced seed yields by 41% at ambient CO_2 but caused no reduction occurred at CO_2+	66
US—Maryland	Winter wheat (*Triticum aestivum* L. cvs. Massey and Saluda) and corn (*Zea mays* L. cv. Pioneer 3714)	No significant interactive effects were observed for either wheat or corn; averaged over two CO_2 treatments, O_3 caused 15%–11% yield loss for wheat and 9% for corn at O_3++ relative to CF; CO_2+ (150 ppm above AA) increases wheat (C_3 crop) yield by 15%–26% and corn (C_4 crop) yield by 4%	91, 92
US—Maryland	Soybean (*Glycine max* L. Merr. cv. Clark)	Leaf photosynthesis rates, plant biomass, pods per plant, and grain yields were stimulated by CO_2+ in the presence of O_3++; the negative impact of ambient O_3 on growth and productivity were largely counteracted by CO_2+; the effect of CO_2+ in combination with O_3 on stomatal conductance appeared to be additive	63
Europe (ESPACE-wheat study)	Spring wheat (*Triticum aestivum* L. cv. Minaret)	No effect on phenological development, rate of leaf emergence, final leaf number, and duration of grain filling by CO_2+ or O_3+; few interactive effects of CO_2+ and O_3+ on tillering and LAI; CO_2+ ameliorated the negative effect of O_3+ on leaf area duration, senescence of the flag leaves during grain filling and yield loss; CO_2+ increased grain yield by up to 33%, a 7-h daily mean O_3 of 60 ppb under ambient CO_2 level did not significantly affect grain yield; CO_2+ does not protect against substantial O_3+-induced yield losses resulting from its direct deleterious impact on reproductive processes	69, 70, 93–98
UK—Sutton Bonington	Potato (*Solanum tuverosum* cv. Bintje	O_3+ was insufficient to reduce tuber yields compared with AA; CO_2+ enhanced crop growth during early stages of the season but had no effect on yield; there was no significant effect between CO_2+ and O_3+ for any of the growth and yield variables examined	73
UK	Spring wheat (*Triticum aestivum* L. cv. Wembley)	CO_2+ fully protected against the detrimental effects of O_3+ on biomass but not yield	99

TABLE 3 (*Continued*)

Location	Crop	Effect	Reference
O_3 and water stress			
US—mid–Ohio River Valley	Common milkweed, white ash, tulip tree, wild grape, black cherry, etc.	In 1988, O_3 levels were high but injury to vegetation was very low because of drought stress; however, in 1989, O_3 levels were much lower, yet optimum growing condition resulted in greater foliar injury	100
US (part of NCLAN)	Soybean (*Glycine max* L. Merr.)	Compared with well-watered regime, soil-moisture stress reduced O_3-induced yield loss; yield loss induced by soil-moisture stress is the greatest when O_3 level is low	101
UK	Kenaf (*Hibiscus cannabinus* L.)	O_3 damage was alleviated by mild water stress but enhanced by severe water stress	102
O_3 with NO_x and/or SO_2			
US (part of NCLAN)	Soybean (*Glycine max* L. Merr.)	No interactions between O_3 and SO_2 found	101
US	Watermelon [*Citrullus lanatus* (Thunb.) Matsum & Nakai]	SO_2 enhanced phytotoxicity of O_3 to watermelon	103
Germany	Spring barley (*Hordeum vulgare* L. cvs. Arena and Alexis); spring wheat (*Triticum* (*aestivum* L. cvs. Turbo and Star)	No consistent effect of any of O_3/NO_x and O_3/SO_2 combinations on any of the crops could be detected across seasons and cultivars; O_3/NO_x and O_3/SO_2 mixtures reduced yield loss to varying degrees; NO_x and SO_2 seemed to act antagonistically to O_3 with one exception	104
Switzerland	Spring wheat (*Triticum aestivum* L. cv. Albis)	NO at low O_3 concentration induced effects on yield and physiological parameters similar to those of increased O_3 concentrations; no adverse effect of NO at higher O_3 concentrations	105
Pakistan	Rice (*Oryza sativa* L.)	O_3 (40–42 ppb for 8 h/day) is more phytotoxic than NO_2 (21–23 ppb for 24 h/day) at the concentrations used; no significant interactions were found	40
O_3, CO_2 and nitrogen (N)			
US—Raleigh	Cotton (*Gossypium hirsutum* L.)	CO_2+ generally stimulated growth and yield whereas O_3 exposure suppressed growth and yield; stimulation induced by CO_2 increased as O_3 stress increased; these interactions occurred for a range of soil N levels	106
Germany	Spring wheat (*Triticum aestivum* L. cv. Minaret)	CO_2+ increased yield by 23% at 120 kg of N and 47% at 330 kg of N; Minaret was not effected by O_3+	107
O_3 and NH_3			
Netherlands	Bean (*Phaseolus vulgaris* cv. Pros)	Adverse effects of O_3+ on biomass and pod yield did not depend on the NH_3 level	72

[a]LAI, leaf area index; NCLAN, National Crop Loss Assessment Network. Other abbreviations as in Tables 1 and 2.

standard protocol for experimental and modeling procedures. Environmental data, i.e., air temperature, global radiation, humidity, and trace-gas concentrations, were also collected and cover a considerable range of values (48).

A summary of the findings of the ESPACE-wheat program with particular regard to the interactive effect between CO_2 and O_3 on responses of spring wheat is summarized in Table 3. Most of the studies on the interactive effect of CO_2 and O_3 found that elevated CO_2 concentrations partially ameliorated the negative effects of elevated O_3 concentrations. Table 3 also includes a summary of the findings of studies focusing on the interactive effects of O_3 and water stress, O_3 with NO_x and/or SO_2, O_3 with CO_2 and nitrogen, and O_3 with ammonia (NH_3). Studies on O_3 and water stress found that soil-moisture stress reduced O_3-induced yield loss because plants close their stomata to conserve water. Synergistic effects of O_3 with NO_x, SO_2, and NH_3 were not consistently detected across studies.

5. SUMMARY OF DIFFERENT EXPOSURE INDICES: STRENGTHS AND WEAKNESSES

A variety of alternative statistical approaches have been examined to summarize the exposure of plants to ambient air pollution. These approaches have become increasingly sophisticated over time. Exposure indices weight exposure duration and peak concentration in a variety of ways.

$$\text{Index} = \sum_{i=1}^{n} w_i \,{}^{*}\mathrm{f}(C_{\mathrm{O3}})_{\mathrm{i}}$$

is the generic representation of the indices. C_{O3} is the hourly mean O_3 concentration, $f(C_{O3})$ is a function of C_{O3}, w_i is a weighting scheme that relates ambient concentrations to flux into the plant, and n is the number of hours over which O_3 concentrations are summed (1).

Figure 3 shows the weighting factors for AOT40, SUM06, and W126. AOT40 is defined as:

$$\text{AOT40} = \sum_{i=1}^{n} [C_{\mathrm{O3}} - 40]_{\mathrm{i}} \quad \text{for } C_{\mathrm{O3}} \geq 40\,\text{ppb}, \quad [\text{AOT40 units: ppbh}],$$

where C_{O3} is the hourly O_3 concentration in parts per billion (ppb), i is the index, and n is the number of hours with $C_{O3} > 40$ ppb over the 3-month growing period that has been set as the evaluation period for arable crops. AOT40 is currently used to define CLs for O_3 to protect crops and natural vegetation, including forests in Europe (see Section 3.2). SUM06 is defined as:

$$\text{SUM06} = \sum_{i=1}^{n} [C_{\mathrm{O3}}]_i \quad \text{for } C_{\mathrm{O3}} \geq 60\,\text{ppb}, \quad [\text{SUM06 units: ppbh}],$$

where parameters are defined in the same way as they are for AOT40. The seasonal SUM06 value is determined by summing hourly O_3 concentrations during three consecutive months of the growing season (1). The precise three months to use is

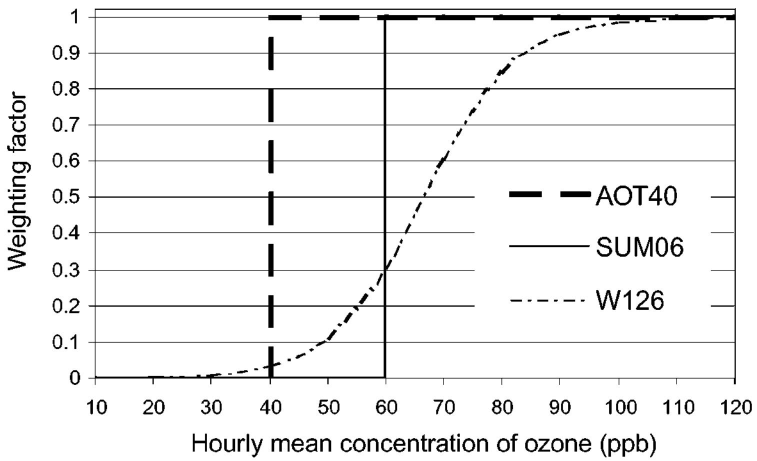

Figure 3 Weighting factors for AOT40, SUM06, and W126.

left ambiguous. SUM06 is favored by researchers in the United States for protection of vegetation. The SUM06 index uses a higher threshold, but once the threshold is reached, it accumulates exposures more rapidly than AOT40. W126 is defined as:

$$\mathrm{W126} = \sum_{i=1}^{n} C_{\mathrm{i}}\,{}^{*}\mathrm{w}_{\mathrm{i}} \quad \text{where } \mathrm{w}_{\mathrm{i}} = 1/(1 + 4403\,{}^{*}\exp(-0.126\,{}^{*}\mathrm{C}_{\mathrm{i}})),$$

[W126 units: ppbh],

W126 is generally viewed as better representing observed yield loss but is more difficult to implement as a regulatory standard.

Figure 4 shows the relative yield loss calculated for wheat, rice, corn, and soybeans using the 7-h and 12-h mean indices, and the cumulative SUM06 and AOT40 indices. These indices are all determined by an empirical fit of data primarily obtained from the open-top container experiments conducted as part of the NCLAN or EOTC programs. The empirical data fit is performed using Weibull or exponential functions that capture aspects of plant response to O_3 that linear functions do not (49). The Weibull function is of the form: $y = \alpha \exp[-(C_{O3}/\omega)^{\lambda}]$ where y is plant response, C_{O3} is O_3 concentration, α is the theoretical yield at zero O_3, ω is a scale parameter on O_3 dose, and λ is a shape parameter (49a).

The indices described above are based on retrospective statistical analysis of data from the US NCLAN and/or EOTC studies. However, by retrospectively analyzing the NCLAN and EOTC data, Legge et al. (51) show that the cumulative frequency of intermediate hourly O_3 concentrations is an important determinant of crop-yield loss (51). This is because moderate O_3 levels frequently occur during periods of the day when stomata are open and crop uptake is high. The NCLAN analysis indicated that the cumulative frequency of occurrence of O_3 concentrations between 50 and 87 ppb is the best predictor of crop response in the United States,

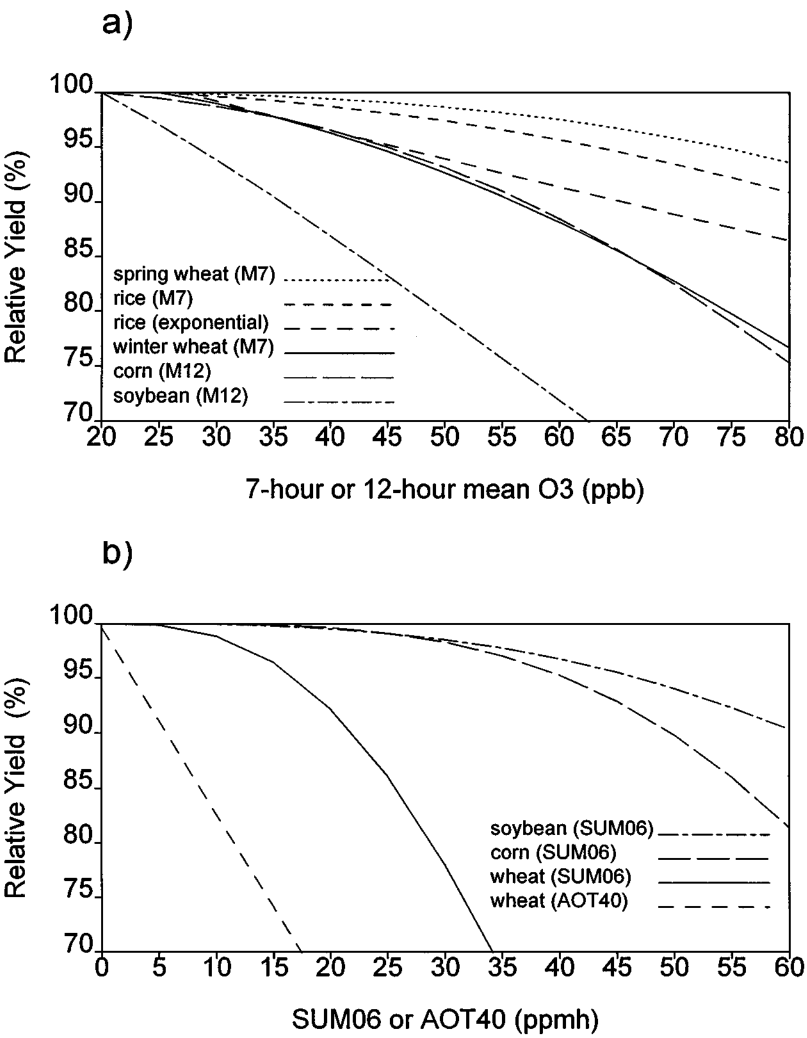

Figure 4 Ozone exposure-response functions for specific crops. (*a*) Exposure-response functions are based on 7-hour (9 AM to 4 PM) mean O_3 concentrations for spring wheat, winter wheat, and rice, and 12-hour (8 AM to 8 PM) mean concentrations for corn and soybean with an O_3 reference level of 25 ppb (20 ppb for 12-hour mean) (49). (*b*) The SUM06 and AOT40 cumulative exposure-response functions use an O_3 reference level of 0 ppmh. All exposure-response functions use a Weibull fit of the data except AOT40 which uses a linear fit; an exponential function was used for one of the rice exposure-response functions in (a). (32, 50; D. Olszyk, personal communication). The US EPA Criteria Document (1) provides the Weibull function coefficients for individual crop cultivars. In the plots shown here, we used an average of the coefficients of all studied cultivars of a particular species to represent the Weibull coefficients for that species.

whereas results from EOTC indicate a range of 35–60 ppb as important in Europe. This supports the idea that different thresholds for O_3 exposure in Europe (40 ppb) and the United States (60 ppb) are appropriate for the standard-setting process. As discussed in Section 3.1, current research in Europe and the United States has begun to focus on developing control strategies based on flux-oriented dose-response relationships (36, 52).

From the best evidence to date, it appears that exposure indices for setting air-quality standards to protect vegetation should (*a*) accumulate hourly O_3 concentrations, (*b*) give preferential weight to daytime concentrations between 0800 and 2000 h, (*c*) give preferential weight to higher O_3 concentrations, and (*d*) account for variations in humidity. There is a trade-off between the most scientifically correct standard/evaluation tool and a standard that is manageable from a policy perspective. However, the research and standard-setting currently under way in Europe provides a useful template for consideration in the United States.

6. ECONOMIC ASSESSMENTS

The US Clean Air Act unambiguously bars consideration of emission control costs from the process of setting air-quality standards (53). It does, however, permit consideration of the costs of damages incurred by air pollution. Costs are also considered when determining how states will meet air-quality standards. A variety of economic assessments have been conducted to evaluate the economic impact of O_3 on agriculture. Several reviews of US-based economic assessments have been conducted (e.g. 1, 22, 54–56). Table 4 summarizes additional studies that were conducted but includes the 1989 study by Adams et al. (49) to represent the US NCLAN study. These studies indicate that ambient O_3 concentrations are imposing substantial economic costs on agriculture. For instance, Adams et al. found that if O_3 is reduced by 25% from what it was during the 1981–1983 period in the United States, the economic benefits would be approximately $US 1.9 billion (1982 dollars) (49). Conversely, a 25% increase in O_3 pollution was estimated to result in costs of $US 2.1 billion.

Although both the US and Europe supported comprehensive research programs on the impacts of O_3 on agriculture (NCLAN and EOTC, respectively), the United States has conducted more-thorough economic assessments. The NCLAN and EOTC studies adopted different approaches, the former designed to provide dose-response information for use in economic assessments and the latter to study the mechanisms of O_3 impact and the interactions of O_3 with other environmental factors. Spash (57) argued that the EOTC program would have been more useful had it been designed to include an economic assessment of O_3 impacts.

The limitations of the earlier economic assessments persist in the later evaluations listed in Table 4. They include limited O_3 data, extrapolation from a limited set of crop and cultivar dose-response data (57), uncertainty about appropriate exposure measures, and potential errors arising from the economic model used (58). However, Adams & McCarl (59) argued that changes in key physical

TABLE 4 Studies on the annual economic damage resulting from the impact of O_3 exposure on crops

Region	Crops	Damage/benefit	Comments	Reference
US	Corn, wheat cotton, alfalfa, forage, rice, soybeans, sorghum	\$1.89 billion (1982 dollars); results similar to Adams et al. (108)	Benefits of 25% O_3 reduction from the average O_3 levels over the years 1981 through 1983 in all regions; welfare approach[a] adopted	49
US	Corn, soybeans	\$17–\$82 million (1992 dollars)	Benefits of meeting O_3 standards of W126 = 20 (75) ppmh are \$17 (50) million; revenue approach[b] adopted	109
US	Corn, wheat, cotton, soybeans, barley, alfalfa, rice, sorghum	\$2–\$3.3 billion (1990 dollars)	Benefits from completely eliminating O_3 precursor emissions from motor vehicles; welfare approach adopted	110
Netherlands	14 crops in the country	\$320 million (1983 dollars)	Consumers' net gain from reducing air pollution (including O_3, SO_2, and HF[c]) to background levels; 70% of crop production loss is caused by O_3	111
Netherlands	All crops in the country	310 million euros (1993–1996 euros)	Benefits of reducing O_3 to the natural background levels; welfare approach adopted	112
China	Rice, wheat, corn, soybeans	\$2 billion (1990 dollars)	Benefits of reducing O_3 to the natural background levels; revenue approach adopted	W&M[d]

[a]Welfare approach refers to mathematical programming models or econometric models based on microeconomic theory (112). It takes into account the response of input and output market prices to the differential changes that pollution control causes in each person's production and consumption opportunities as well as the input and output changes that those affected can make to minimize losses or maximize gains from changes in production and consumption opportunities and in the prices of these opportunities (55).

[b]Revenue approach is a simple multiplication technique that equates damage to change in yield multiplied by a fixed market price. It assumes no change in producer acreage and input decisions or in market prices. Adams et al. (113) find that the simple multiplication technique overestimates the damage by 20% as a result of its failure to account for mitigating adjustments as well as partially compensating price effects.

[c]HF = hydrogen fluoride.

[d]X. Wang & D. L. Mauzerall, manuscript in preparation.

parameters had to be substantial if they were to alter benefit estimates significantly, given the extent of the NCLAN study. The interactions of O_3 with CO_2 and water stress are important (see Table 3 for description of effects between O_3 and other environmental factors) but were not included in any of these studies.

It is difficult to directly compare numerical cost estimates between studies because the sources of O_3 pollution that are evaluated, the crops that are considered, the dose-response functions that are used, and the assumed economic environmental conditions differ considerably. In addition, considering aggregated effects of O_3 on agriculture can be deceptive (56). For example, in US studies where national effects are reported, the significant impacts of O_3 in the San Joaquin Valley of California may be obscured. High-level studies both in the United States and in

Europe can obscure significant differences in regional effects of O_3 because of both regional variations in ambient O_3 levels and variations in the importance of O_3-sensitive crops produced within the region.

Using a simple welfare approach, we estimate that O_3 pollution in the year 1990 may have resulted in decreased yields of four major grain crops in China worth approximately $2 billion (1990 dollars) (X. Wang & D.L. Mauzerall, manuscript in preparation).

7. RECOMMENDATIONS FOR FUTURE RESEARCH

Substantial progress has been made in the past 20 years on understanding how exposure to O_3 reduces crop yields and damages vegetation. However, there are many areas where research is just beginning. The following is a list of areas where further knowledge would be particularly valuable.

More systematic and extensive work is needed on crop strains that are used in the developing world. These strains may be different from those used in the United States and Europe, where the large-scale systematic studies have been conducted. In addition, O_3 monitoring is needed in developing countries to determine O_3 levels outside urban regions.

To date there has been little work coupling projected increases in tropospheric O_3 in developing countries with impacts on agricultural yields. Work in this area has started with the use of global and regional chemical tracer models that calculate O_3 concentrations globally to examine the impact of surface O_3 on crop yields in China (42, 43; X. Wang & D. Mauzerall, manuscript in preparation). With the likely increase of emissions of both greenhouse gases and reactive air pollutants, this is becoming increasingly important.

Given the probable increase in O_3 concentrations in large parts of the northern hemisphere, it may be worthwhile to evaluate the feasibility of developing crop strains that are more resistant to O_3. Although in traditional breeding programs air pollution resistance has not usually been targeted as a desirable trait, the prospect of breeding plants with enhanced resistance to common air pollutants is beginning to be examined (20, 61). Because different cultivars of the same crop species vary in their sensitivity to O_3, it should be feasible to select and breed plants with enhanced resistance. In the future, biotechnology could be used to enhance resistance to air pollutants, but before identification of gene(s) controlling O_3 sensitivity can be determined, the principle mechanisms underlying the sensitivity/resistance to O_3 must be better understood (61). In addition, an important question to address is whether making use of O_3-resistant cultivars would result in a trade-off of such desirable characteristics as flavor, nutritional content, etc., in the crop. The general consensus of the scientific community, as summarized in the US EPA criteria document, is that because of the variety of detrimental effects O_3 imposes on natural ecosystems and human health, top priority should be given to solving the problem of O_3 pollution at its source and not by selecting pollution-tolerant cultivars (1).

Relatively little research has been conducted on the impact that elevated O_3 has on natural vegetation, forests, and ecosystems. A better understanding of how O_3 impacts natural vegetation is needed.

Both experimental and modeling work under different environmental conditions (such as variations in humidity, soil type, temperature, etc.) are needed. Effect of factors such as variation between species and strains, variations in climate and soil type, the timing of O_3 episodes relative to the stage of plant growth, and effect of water and heat stress could be quantified with further work. Methods to relate the ambient O_3 concentration to O_3 flux into the plant and to relate this flux to detoxification, photosynthesis, and plant productivity are still needed. An elucidation of these mechanisms would be beneficial both for qunatifying the impact of O_3 on crops and on natural vegetation. O_3 flux measurements and O_3 exchange simulations for representative ecosystems would be valuable for establishing control strategies based on flux-oriented dose-response relationships.

8. SUMMARY AND CONCLUSIONS

Scientific evidence indicates that vegetation and human beings are sensitive to O_3 in different ways. Most crops in the world are grown in the summer when O_3 photochemical production and resulting concentrations are at their most elevated and are frequently sufficient to reduce crop yields. To date, despite a need for a more appropriate secondary standard to protect vegetation, in the United States the primary and secondary standards have been set equal to each other. This was initially due to an early lack of research on the impacts of O_3 on vegetation, and later to the view that implementation of a long-term cumulative O_3 standard would be more costly and difficult to enforce than a short-term standard.

There is now substantial scientific evidence of the mechanisms and dose-response relationships of O_3 on agriculture. The implementation of a long-term cumulative O_3 standard has occurred in Europe and is more feasible today than it was in 1978, when the first NAAQS were set in the United States. As part of the NAAQS review process, which occurs every 5-years and is currently underway, the US EPA has an opportunity to consider a more sophisticated peak-weighted cumulative O_3 secondary standard. Research to measure and develop flux-based models that account for the influence of VPD, temperature, and radiation and that can be parameterized to estimate flux into plants over extensive geographic regions would be valuable. Such research is beginning in Europe and may successfully contribute to the development of level 2 standards for O_3 protection that could provide a useful template for a similar standard-setting approach in the United States.

Identifying crop loss as an impact of air pollution to the governments of developing countries may help motivate an evaluation of emissions from combustion processes. It is possible to simultaneously reduce the emissions of NO_x, the primary precursor of O_3, and of CO_2, the primary greenhouse gas, by either increasing energy efficiency or moving to noncombustion based energy sources. Thus it may be possible, by addressing regional O_3 pollution, to obtain both a local air-quality benefit and global climate benefit.

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