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NATIONAL AMBIENT AIR QUALITY OBJECTIVES FOR GROUND-LEVEL OZONE

SCIENCE ASSESSMENT DOCUMENT

A Report by
the Federal-Provincial Working Group
on Air Quality Objectives
and Guidelines

July, 1999

Canada

8 EFFECTS ON VEGETATION

The information presented in this chapter has been extracted from the Report of the Vegetation Objective Working Group of the NO_x/ VOC Science Assessment (Multistakeholder NO_x/VOC Science Program, 1997, VOWG). The mandate of this group was to review the current state of knowledge on ozone damage to Canadian vegetation, and to develop a position on the appropriate form and level of an ambient ozone air quality objective to protect vegetation. Given this mandate, and the VOWG's understanding of the revised framework for setting ambient air quality objectives in Canada (see Preface), which involves first, identification of Reference Levels, the VOWG report focussed on providing the information that would form the scientific basis for setting a Reference Level for ozone effects on vegetation. Subsequent to the VOWG review, the literature was reviewed to end of 1997 and relevant material included in this assessment.

8.1 QUALITATIVE TOXICITY ASSESSMENT

Photochemical oxidant air pollution was first recognized in 1944 when Middleton et al. (1950) observed toxic effects on vegetation in Los Angeles. These symptoms most closely resembled those caused by peroxyacetyl nitrate (PAN) or by mixtures of PAN, aldehydes and other highly oxidizing chemicals. Later, Richards et al. (1958) ascribed grape 'stipple' near San Bernardino, California, to atmospheric ozone. Tobacco 'weather fleck' observed at Beltsville, Maryland, in 1952 and in southern Ontario in 1955 was attributed to ozone in 1959 (Heggestad & Middleton, 1959; MacDowall et al., 1963). Etiological studies to determine the relationship between atmospheric ozone and unexplained needle injuries on Eastern white pines were started in Canada in 1959 (Linzon, 1966) and in the U.S. in 1961 (Berry & Ripperton, 1963).

Although ozone injury was first observed and documented under field conditions in the Los Angeles area, the majority of research that followed through the 1950s to the 1970s was conducted with pot-grown plants under greenhouse or controlled environment conditions. The advantages of this approach were good reproducibility under specific pollutant exposure and climatic regimes, exhaustive evaluation of exposure-response functions, and, in some cases, detailed examination of the physiological, biochemical and morphological effects of the pollutant on the receptor. However, as research efforts gradually began to focus on the biological relevance of the early findings, more effort was directed towards field exposure studies, and a search for meaningful exposure functions that would enable policy setters to predict the impact of season-long ozone exposure on agricultural and forestry industries.

Plant response to ozone is based on a sequence of biochemical and physiological events that can result in foliar pathologies (visible injury), altered carbohydrate allocation leading to reduced growth and yield, as well as impacts on the competitive relationships within plant communities and ecosystems (Guderian et al., 1985). These types of effects are summarized below.

8.1.1 Biochemical, Metabolic and Physiological Effects

The effects of ozone on the biochemical, metabolic and physiological processes of plants have been extensively reviewed and discussed in recent publications (Runeckles & Chevone, 1992; Guderian, 1985; Legge & Krupa, 1986; Unsworth & Ormrod, 1982; and Darral, 1989). Accordingly, these documents have been used in the development of the overview summary that follows. Unless otherwise or specifically cited, the source of the following material should be ascribed to all of these excellent review publications.

Ozone can affect a fairly wide array of cellular processes once it has entered the leaf via open stomata. Once inside, the dividing line between biochemical and physiological effects is difficult to differentiate since the resulting physiological effects have their origins in the chemical reactions of ozone with cellular constituents. Under certain conditions, resistance or detoxification mechanisms can alter the entry of ozone into the plant leaf or result in its initial detoxification once inside the intercellular air spaces and mesophyll cell walls (i.e., the apoplastic space outside the plasmalemma). Once inside the symplast, ozone that has not been detoxified in the apoplast acts first at the biochemical level to impair the functioning of various cellular processes.

The current understanding of resistance or detoxification mechanisms is still in a state of relative uncertainty. Under certain conditions, physiological responses to ozone exposure may protect the plant by excluding ozone from the leaf interior. Specifically, exposure to very high levels of ozone can result in reductions in rates of stomatal conductance. The mechanism is not well understood, but it has been shown in one study to be related to histological changes in guard cells and resultant loss of stomatal control. This response is often labeled as an exclusion or resistance mechanism. Reductions in stomatal conductance in plants exposed to lower concentrations of ozone have been attributed to increased internal leaf CO_2 concentrations, resulting from ozone-induced reductions in biochemical CO_2 fixation; however, more research is needed in this area, as some evidence also exists that under certain conditions, ozone can cause stomatal opening.

Some degree of oxidation and cleavage of waxes at the leaf surface can occur and this can lead to changes in composition and physical properties of the leaf surface (e.g., decreased water repellence); it would also result in reduced ozone levels available to enter plant leaves. Once inside the intercellular air spaces and mesophyll, ozone is thought to persist mainly as O_3, although superoxide anion and hydroxyl radicals are also formed. These oxidant species are reactive with cellular components, such as ascorbate, olefins such as ethylene, terpenoids, hydroxyl ions, as well as major cell-wall constituents such as cellulose, lignin and pectins. Because these oxidant species are additionally produced in the cell as a result of photosynthetic processes, and are injurious to cell constituents, plant cells have evolved enzymatic mechanisms to transform these oxidative species to less toxic constituents. Ascorbate, peroxidase, glutathione reductase and superoxide dismutase, to name the most commonly cited (Runeckles & Chevone, in Lefohn, 1992), are assumed to have some role in detoxifying oxidant species resulting from ozone exposure, as well as those resulting from normal cellular activity.

There are conflicting studies regarding the role of superoxide dismutase in the reduction of products from ozone interactions with the cytoplasm; there are also reports of increased peroxidase activity and decreased diamine oxidase activity that could reduce the impact of ozone by increasing the scavenging of potentially harmful hydrogen peroxide and by increasing di- and polyamine levels. In any event, these **"**detoxification**"** enzymes are saturable, and as they are oxidized themselves in the process of reducing oxidative species, require cycling back to the reduced state before being available for further detoxification 'work'. The reduction of these enzymes requires a reductant (NADPH, reduced ferredoxin, etc.), a number of which are formed by energy requiring processes in the mitochondria.

These exclusion or detoxification mechanisms certainly reduce the amount of ozone which can react with photosynthetic and respiratory components. The role of exclusion and detoxification mechanisms in differential ozone sensitivity among species or cultivars is not well understood, in that there does not appear to be a unifying model of how resistance is acquired by a plant. It seems clear that detoxification of ozone or its products would burden the cells' energy budget, although whether this additional burden would decrease productivity, relative to direct effects of ozone on photosynthesis for example, is not known.

In their review, Runeckles and Chevone (1992) have further subdivided the biochemical effects into the following functional areas:

Chloroplast metabolism

- effects on sulfhydryl groups and enzymes of the reductive pentose cycle;
- direct reaction of ozone with ascorbate, resulting in its removal as a peroxidase substrate and the potential generation of hydrogen peroxide;
- effects on chloroplast ATP levels and an influence on the dark reactions of the Calvin cycle in the stroma;
- decreased Hill reaction activity;
- indirect effects on Photosystems I and II;
- possible effects on nitrogen metabolism;
- chlorophyll destruction; and
- effects on the integrity of the envelope and thylakoid membranes that perturb the chemi-osmotic status and the balance of proton and other ionic flows.

Photorespiration and Respiration

- changes in the mitochondrial structure can affect the respiration process; and

- photorespiration, involving reactions within the chloroplast, the cytoplasmic glyoxysomes and the mitochondria, can be affected by alterations in the oxygenase function of rubisco (with impacts on CO2 release).

Carbohydrate Metabolism

- effects on enzymes related to carboxylase and oxygenase functions within the rubisco process can lead to effects on carbohydrate translocation and the carbon and energy economies of the plant.

Nitrogen Metabolism

- effects on nitrate reductase activity within the chloroplast and on glycine and serine within the photorespiratory pathway;
- changes in nodulation of the roots of legumes related to the supply of photosynthate from the shoots; and
- possible ozone scavenging due to effects on polyamine generation via diamine oxidase inactivation.

Organic Acids and Lipids

- possible changes in lipid and fatty acid fractions resulting from direct chemical reactions with ozone (lipid decomposition and formation of malondialdehyde) or indirectly via alterations in respiration, photorespiration and amino acid metabolism.

Secondary Metabolism

- although very little direct evidence has been published, the role of ozone in the generation of phenolics, flavonoids, alkaloids, terpenoids, betalains and glucosinolates, which are linked with foliar pigmentation and senescence processes appears to be important.

The major physiological processes affected by these alterations are reductions in photosynthesis and increased leaf senescence. The effects on photosynthesis include impacts on stomatal conductance, photosynthetic capacity, carbohydrate allocation and respiration. The photosynthetic capacity of a plant plays a major role in plant response to stresses in the environment and is also associated with foliar nitrogen content and with water movement, both of which are, in turn, related to carbohydrate allocation. As a result, reductions in photosynthetic capacity have the potential to adversely affect growth patterns, leaf repair and overall growth and reproductive capacity. One of the major impacts of altered carbohydrate allocation is on the availability of carbohydrate resources to the roots and associated mycorrhizal fungi, as the plant tries to meet the needs of foliar repair or redirects carbohydrates towards increased leaf production to compensate for foliar loss resulting from ozone stress. Ozone induced changes in canopy density, root/shoot ratios and stem growth also can affect the functioning of the plant and render it more susceptible to other stresses.

In their summary of the effects of ozone on cellular permeability and leakage, Runeckles and Chevone (1992) provide an overview of the linkages that must be taken into consideration in the overall evaluation of ozone impacts on plant growth:

> *Although changes induced by ozone may involve specific chemical reactions that exert direct effects on metabolic processes, it is important to recognize that many effects may be mediated by changes in membrane structure and function that profoundly influence the physiology of the affected cells, the tissues in which they occur, and, hence, the plant as a whole. Plant responses that result in visual changes in foliar characteristics are secondary processes of ozone toxicity, which appear after initial defense mechanisms are overrun. Cellular biochemical and physiological alterations occur without such visible injury symptoms appearing, and these modifications affect critical metabolic functions capable of limiting oxidative stress and ozone toxicity both directly and via more complex physiological interactions within the cell. It is the integrated cellular system that confers and determines plant sensitivity to ozone.*

8.1.2 Acute and Chronic Foliar Injuries

As with many other pollutants, ozone effects on plant foliage can be categorized into acute and chronic effects. Acute symptoms on broad-leaved plants consist of chlorosis, fleck, stipple and uni- or bifacial necrosis. On conifers, acute responses consist of mottle, banding and chlorosis (Krupa & Manning, 1988). Plants have the capacity to compensate for acute effects, depending on the respite time between acute exposures and on plant phenology when the initial stress occurred (Lefohn & Runeckles, 1987).

Chronic symptoms are related to frequent, relatively low hourly ozone concentrations, with periodic, intermittent peaks of relatively high hourly concentrations. Chronic effects can lead to changes in plant growth, productivity and quality, and these effects may occur without visible symptoms. When symptoms do develop, they can include chlorosis, delayed early season growth, premature senescence and leaf abscission (Manning & Krupa, 1992). In the case of acute effects, plants can compensate for stress during respite periods; therefore, the frequency of ozone episodes and the time interval between such episodes are critical in evaluating and modelling plant response (Krupa & Kickert, 1989; Lefohn & Runeckles, 1987).

It is well established that foliage is the primary site of plant response to ozone exposure. It is also known that ozone exerts a phytotoxic effect only if a sufficient amount reaches sensitive sites within the leaf. Thus, ozone injury will not occur if the rate of uptake is low enough that the plant can detoxify the ozone or is able to repair or compensate for the effects (Tingey & Taylor, 1982). Effects at the cellular level are ultimately expressed as visible injury to the leaf or as secondary effects that can be expressed as reduced root growth, reduced yield of fruits or seeds, or both. The main factor in the ultimate impact of ozone exposure on growth or yield of individual plants involves a determination of whether ozone directly or indirectly impacts a metabolic or physiological process that is or may become a limiting factor in plant growth at the time of exposure.

Exhaustive lists of plant foliar sensitivity/resistance to ozone under short-term, controlled-environment conditions have been published (Guderian et al., 1985; Heck et al., 1977). However, there is uncertainty surrounding the relationship between plant foliar injury and life cycle yield and biomass alteration resulting from season-long ozone exposure under field conditions.

There is still interest in some of the earlier exposure-response information on foliar injury, as this may assist decision - makers in the development of short-term protection for crops or other types of plants where injury can affect marketability or aesthetic values. Comprehensive reviews of the available literature were made by Jacobson (1977) and Linzon et al. (1975), and concentration-time profiles for short exposure, acute foliar injury were developed for sensitive, intermediate and resistant species. This three-tier classification system is of limited use in terms of its direct application to current crop species and cultivars. Much of the information came from genetic lines and plant species that were chosen for study due to their sensitivity to ozone; the classification system is quite old; and most of these lines and cultivars are no longer in commercial use. However, the classification system does provide benchmark information that should be considered in any effort to develop ozone air quality objectives.

Based on these and other findings, Guderian et al. (1985) developed a set of maximum acceptable ozone concentrations, which, if met, would provide reasonable protection of vegetation from short term, acute exposures. These thresholds are shown in Table 8.1.

Table 8.1 Exposure thresholds for plant response (foliar injury) to ozone (from Guderian et al., 1985).

Duration of exposure (hours)	Ozone concentration by category of plant resistance (ppb)		
	Sensitive	Intermediate	Resistant
0.5	150	250	500
1.0	75	180	250
2.0	60	130	200
4.0	50	100	180

8.1.3 Growth, Yield and Productivity Impacts

Crops

The importance of short-term, controlled-environment ozone exposures and associated thresholds for foliar response has been overshadowed in the last 10-15 years by the shift in research priorities to natural, ambient exposure assessments under full season, field grown conditions. The main reason for this shift was the growing body of evidence that indicated foliar injury was not an acceptable surrogate for ozone impacts on crop yield or tree growth. In many studies, significant reductions in yield or biomass growth were being detected in the absence of foliar symptom development, while in other cases, plants were able to sustain considerable foliar injury with no detectable loss in yield or productivity (U.S. EPA, 1995).

With the trend away from foliar injury assessment, the concept of 'damage' has developed (Guderian et al., 1985) as a measure of impairment in the intended use of the plant. This includes reductions in aesthetic values, the occurrence of foliar injury, and loss of weight, number, or size of the plant part intended for harvest. Loss in yield may also include changes in physical appearance, chemical composition, or the ability to retain quality features during storage. Loss of aesthetic value includes negative impacts on the appearance and marketability of ornamental plants or crops in which the foliage is paramount.

Any assessment of yield or quality parameters under field conditions is complicated by the ubiquity of ozone exposure, the effect of meteorological variables on ozone distribution within crop canopies, and the effect of numerous biotic and abiotic factors which can alter plant response. Some of these difficulties have been partially overcome by refinements made in the field assessment techniques, including open-top chambers, open air fumigation systems, and ambient air pollutant gradients (Ormrod et al., 1988). To date, however, no one research technique has solved all of the problems associated with research on this regional-scale, ubiquitous pollutant.

A comprehensive program designed to address the issue of season-long ozone impact on agricultural crop yield was the National Crop Loss Assessment Network (NCLAN) in the U.S. This seven-year program (1980-86) was initiated by the Environmental Protection Agency in 1980 and consisted of experimental exposures of 38 different crop species/cultivars at five geographic sites, chosen to represent distinctly different climatic conditions in regions growing different crop species. Open-top chambers were used to expose different agricultural crops to various regimes of ozone and sulphur dioxide. Plant yields were measured to determine exposure-response relationships and to assess the national economic consequences resulting from the exposure of major agricultural crops to ozone. The results of this program are described in numerous publications (Heck et al., 1982, 1983, 1984a, 1984b).

In the U.S. EPA criteria document on ozone impacts (1986), the review of all NCLAN and related yield response studies resulted in the following main conclusions:

- current ambient levels of ozone in many parts of the U.S. are sufficiently elevated to impair the growth and yield of plants;
- the NCLAN study and supporting field studies using chemical protectants show that effects on plants occur with only a few hourly ozone concentrations above 0.08 ppm;
- the growth and yield data further confirm that several plant species exhibit growth and yield effects when the mean ozone concentrations exceeded 0.05 ppm for daily 4-6 hour periods for at least two weeks;
- data from NCLAN exposure-crop response regression analyses indicated that at least 50% of the species/cultivars tested were predicted to exhibit a 10% yield loss at 7-hour season mean ozone concentrations of 0.05 ppm or less.

These findings have been confirmed in the most recent U.S. EPA assessment of yield and productivity impacts due to ambient ozone in the U.S. (U.S. EPA, 1996).

The other coordinated assessment of ozone impacts utilizing open-top chambers and chemical protectants was the European Open-Top Chamber Programme (EOTCP). Details on the findings from these studies are summarized in workshop proceedings (Ashmore & Wilson, 1993; Fuhrer & Achermann, 1994, ICP-Crops Coordination Centre, 1996).

Ornamentals

There have been a number of experimental studies designed to examine the effect of ozone on woody and herbaceous ornamental plants. Some of the herbaceous species examined include: petunia (Craker, 1972), carnation (Feder, 1970), geranium (Feder, 1970), poinsettia (Manning et al., 1973), chrysanthemum (Klingaman & Link, 1975; Brennan & Leone, 1972), turfgrass (Wilton et al., 1972) and begonia, coleus, snapdragon, marigold, celosia, impatiens and salvia (Adedipe et al., 1972). The results of these studies have shown a considerable degree of cultivar sensitivity with effects ranging from growth depression, alteration of plant habit, retardation of floral initiation as well as reductions in flower production. However, in many of these studies, ozone exposure concentrations were unrealistically high or of short duration, making extrapolation of impact to natural exposure under field conditions difficult. Even if these studies had been conducted under exposure conditions characteristic of those encountered in the field, it would be difficult to assess the economic impact of these aesthetic impacts.

Experimental progress in the case of woody ornamentals has been more advanced than for herbaceous species because many species play a dual role, being both ornamental and forest stock. As ornamentals, the majority of trees and shrubs are planted singly, exposing them fully to ambient air. This contrasts with the forest situation where a variety of canopy and stand factors must be quantified before valid extrapolations to natural settings can be made. As a result, much of the forestry oriented experimental research that has been conducted on tree seedling response to ozone has even greater value in terms of woody ornamental effects.

In a review of the tree seedling research reported up to 1986, Pye (1988) summarized ozone effects on biomass, height and photosynthesis for 43 tree species or hybrids. On the basis of this summary, and on additional work published since that time (Chappelka et al., 1988a, 1988b; Reich et al., 1987, 1988; Elliott et al., 1987; Hogsett et al., 1995; Hildebrand et al., 1996) there is convincing evidence that ozone exposures common to some areas of Canada have the potential to cause foliar injuries and growth reductions in many sensitive landscape trees.

Tree species common to Canada that have demonstrated ozone sensitivity (biomass, height, photosynthesis) under controlled ozone exposure conditions include: maples (sugar, silver, red), ash (white, green), spruce (white), white pine, poplar (hybrid), cottonwood, cherry, walnut, sycamore, white birch and red oak. Although ozone impacts varied significantly (reductions and stimulations) in many of the experimental studies, the response to seasonal mean exposures in the 40-60 ppb range for over half of the studies was reported as at least marginal growth reductions (Pye, 1988).

There is also considerable evidence that ozone can injure many annual and perennial grass species commonly used in turfgrass production in parts of Canada (Elkiey & Ormrod, 1980; Richards et al., 1980).

Forest Trees and Unmanaged Native Species

There are many different parameters and limiting factors, which must be considered in evaluating and quantifying the effects of ozone on forest trees and natural vegetation versus agricultural crops. Trees are long-lived perennial plants that are exposed to ozone repeatedly during the year over several years and, unlike agricultural crops, are not usually subjected to fertilization, irrigation, pesticide application or other cultural practices that can moderate their response in the field. Assessment of adverse effects of ozone on seedlings or young trees can be evaluated under experimental conditions; however, the large size of trees at maturity precludes experimental dose dispensing in exclusion chamber studies or the use of protective antioxidant sprays. These factors have limited the assessment of ozone impact to visual observations of foliar injury, and radial and height growth characteristics of individual trees in the stand. Where growth analysis is undertaken from different stands on the basis of air quality gradients, the data must then be considered in terms of edaphic and climatic site variation and related to ozone dose information, where available. Another complicating factor which must be addressed when assessing the overall impact of ozone on forest growth and yield is the process of inter- and intra-plant species competition and possible alterations in successional processes and species composition. In this regard, an adverse effect on the growth or survival of one tree species could have either a beneficial or detrimental effect on the growth or survival of another species, thereby increasing or decreasing the total productivity of a mixed forest stand.

On the basis of experimental chamber exposures to ozone, many tree species indigenous to eastern North America are classified as being susceptible to foliar ozone injury (Davis & Wood, 1972; Davis & Coppolino, 1974; Davis & Wilhour, 1976; Skelly, 1980). Direct injury to tree foliage by ozone has been demonstrated repeatedly in experimental situations, and in nature as well. Concentrations of ozone, at least in some forested areas, are sufficient to cause injury (Linzon, 1973; Miller, 1983; Skelly, 1980). As indicated, these ozone effects can alter the productivity, successional patterns, and species composition of forests (Smith, 1980) and enhance activity of insect pests and some diseases (Woodwell, 1970). The status of ozone-induced effects on temperate and Mediterranean forest tree species, communities and ecosystems was summarized by Skelly (1980), who concluded it is possible that primary productivity, energy resource flow patterns, biogeochemical patterns and species successional patterns may all be challenged by oxidant air pollution.

In a thorough review, Pye (1988) summarized experimental approaches, discussed tree response data from controlled fumigations and evaluated the difficulties in extrapolating experimental findings to regional, economic damage estimates.

In terms of experimental design, indoor growth chambers, greenhouses and continuously stirred tank reactors (CSTRs) have been the most commonly employed forest research technique. Outdoor exposures have used open-top chambers, branch chambers and, occasionally, chamberless designs. Although these techniques offer some control of airflow, temperature and humidity, there are still limitations in using these data for forest productivity assessment (Skärby & Karlsson, 1996; Heck & Cowling, 1997).

Before any attempt is made to extrapolate data from controlled experimental studies to the forest stand, a number of other factors must be assessed. These factors were summarized by Pye (1988) and include changes in stand regeneration, mortality, growth rates and wood quality (strength and pulp yield). Pye also points out that caution must be exercised in extrapolations based on foliar injury assessments. As was the case with agronomic species, tree growth reduction can occur without visible symptoms (Reich & Amundson, 1984, 1985; Reich et al., 1986); visible symptoms can occur without growth impacts (Jensen & Dochinger, 1974, McClenahen, 1979; Patton, 1981) and rankings of species susceptibility based on growth measures do not always correlate with rankings based on foliar symptoms (Jensen, 1973; Jensen & Masters, 1975; Kress & Skelly, 1982). This latter finding is important, since lack of growth reductions with a decreased photosynthetic area suggests compensations in carbon allocation and respiration. Another factor is the possibility that subtle growth reductions were missed due to experimental variability and inadequate error control (Wang et al., 1987) or because several seasons of exposure may be needed to demonstrate impact (Runeckles & Wright, 1996).

In his review, Pye (1988) evaluated biomass growth, height growth and photosynthesis by using data from 25 published experiments on seedlings of 43 tree species and hybrids. On the basis of these studies, it has been clearly demonstrated that ozone reduces tree growth significantly at concentrations common to many areas of the U.S. These concentrations are common throughout several areas of Canada also. Pye pointed out that in the growth response analysis, the statistical power of the study designs is a critical consideration for exposures near ambient concentrations, which are expected to result in subtle changes in plant growth. To date, problems with statistical design, genetic and environmental variability, and exposure duration have prevented the detection of significant growth reductions below about 9%. In addition to the comprehensive review of the experimental data, Pye summarized the factors that limit the extrapolation of these short-term data to longer growth cycle conditions, to mature trees and, subsequently, to stand level yield. These difficulties have been summarized below:

Extrapolating from Short-Term to Long-Term Exposures

- As trees vary in their response to and recovery from ozone over time, the length and timing of the exposure and subsequent data collection can significantly alter the experimental outcome and conclusions.
- As leaf phenology differs significantly between determinate and indeterminate tree species, the impact of ozone for a short duration will vary, depending on species type and exposure regime.
- As most conifers retain their foliage for periods well in excess of a year, the impact of a short duration ozone exposure during only part of this period is of limited value in terms of the full life-span of the foliage.

Extrapolating from Seedlings to Mature Trees

- As the balance (ratio) between metabolically active (photosynthetic) and catabolically (respiration) dominant tissues decreases with age, the impact of ozone early in the life of a tree may not directly translate into equivalent effects later in the growth cycle.
- As the micro-environment in which a leaf grows affects its morphology, resulting in large differences within a mature canopy, the impact of ozone on a uniform set of seedling leaf types may not represent the complete range of foliar response within a mature canopy.
- As water and nutritional transport and storage differ between young and old trees as cambial reserves increase, this may affect daily and seasonal patterns of stomatal conductance and influence ozone uptake and tree response.

Extrapolating from Individual Trees to Forest Stands

- As the distribution of tree sizes in a stand directly affects timber value, and as ozone impacts may directly or indirectly affect this gradient, stand volume and size distribution could be disproportionately altered; of key concern is whether stand processes will compensate for or amplify impacts on individual trees.
- As ozone susceptibility of dominant and suppressed trees within a stand will vary depending on a host of phenotypic and genotypic factors, ozone impact assessment at the stand level requires a more comprehensive understanding of stand dynamics, microclimate, genetic composition and site quality than is provided from seedling level experimentation.

A considerable body of literature has been published on forest tree seedling response to ozone since the review of Pye (1988). A recent summary of the literature prepared by Legge and Krupa (1995) identified some 17 different ozone exposure systems or protocols/methodologies used since 1985 in tree response studies. Sixty-seven citations represented experiments with 27 tree species/varieties, mostly as seedlings in chambered systems. Only four citations, two ambient exposures and two controlled ozone applications, comprised field experiments.

Duration of chambered-experiments, usually open-top, lasted from weeks up to five years in at least one case (Billen et al., 1990). One recent study (Runeckles & Wright, 1996), using a field-situated chamberless ozone exposure system, emphasized the need for multi-season experimentation in which the potential adverse effects of modest increases in ozone concentrations can be properly evaluated.

The central difficulty with respect to forest effects remains the issue of extrapolation and scaling-up of seedling data to the forest stand or ecosystem. Legge and Krupa (1995) have discussed the difficulties presented by Pye (1988) and their comparison of six general characteristics of seedlings with mature trees provides an additional level of relevant detail. The importance of changes in root morphology/function in the dynamics of carbon allocation as a tree ages cannot be underestimated, yet few data are available on below-ground response to ozone. Studies of seedlings are believed by some researchers (Samuelson & Edwards, 1993) to underestimate the sensitivity of larger and more physiologically mature trees. However, this is not yet an area of general consensus or scientific agreement.

Within a deciduous canopy, leaf position also may influence sensitivity of physiological processes. Hanson et al. (1994) noted that extrapolations of seedling-derived data to foliar responses of mature forest trees may lead to the introduction of large errors when predicting mature tree response to ozone. The definition of what constitutes a mature tree may be confounded in the case of some deciduous tree species, as ozone symptom expression was found in at least one study to be similar between overstory and sapling trees (Hildebrand et al., 1996).

In order to overcome some of the limitations which have been described for controlled environment, single species and seedling-age research, other approaches to the evaluation of ozone impacts have focused on regional scale, growth analysis studies (Ohmart & Williams, 1979; McLaughlin et al., 1983; McLaughlin, 1985; Adams et al., 1985; Cook, 1985 and Benoit et al., 1982) and evaluations of ozone levels in forested areas (Pinkerton & Lefohn, 1987). Significant ozone-related decreases in radial growth have been detected in only a few cases where ozone levels normally exceed those normally encountered in Canada and where ozone injury symptoms have been observed and documented during the past 20 years (Peterson et al., 1987; Miller, 1983). In these cases, particularly in the classic link between ozone and growth of Ponderosa pine in southern California (Miller & McBride, 1975), diagnosis of the cause of radial-growth decline was made easier by regional-scale visual changes in forest condition. Despite an apparent growth decline in large areas of the approximately 25 million hectares of southern pine forests where ozone concentrations are often elevated, diagnosis has been difficult due to the lack of a gradient in visible injury superimposed along a strong ozone gradient (Barnard et al., 1990).

Recently, however, sensitive dendrometer bands were used to elucidate the contribution of ambient ozone over five years to the seasonal growth patterns of mature loblolly pine trees in eastern Tennessee (McLaughlin & Downing, 1996). Statistically significant influences of ambient ozone on stem growth patterns were identified even though levels of ozone, rainfall and temperature varied widely over the period. Observed responses to ozone were rapid and occurred within 103 days after exposure to ozone at >40 ppb (McLaughlin & Downing, 1996). Interestingly, this response threshold is similar to that (45 ppb ozone as a 12-hour mean) suggested by Taylor (1994) for seedlings. McLaughlin and Downing (1996) concluded that relatively low levels of ozone could reduce growth of mature forest trees and that interactions between ozone and climate are likely to be important influences on future forest growth in the region. In the northeastern U.S., there is growing evidence that ambient ozone concentrations often exceed the levels that appear to cause injury for some important forest tree species (Hildebrand et al., 1996).

Definitive conclusions concerning the role of ozone in recorded growth reductions are still not possible in other, less severely impacted areas of North America due to the difficulty involved in experimental resolution and in partitioning these effects from other variables that also affect tree growth.

8.1.4 Co-occurrence Effects with Other Ambient Pollutants

Because plant life in nature is rarely exposed to the influence of only one air pollutant, extensive efforts were initiated in the mid-1960s whereby plants were subjected to combinations of ozone with sulphur dioxide, nitrogen dioxide, PAN (peroxyacetyl nitrate) and, later, simulated acid rain or fog, ultraviolet light, carbon dioxide and other components related to possible climate change. The results of these multiple exposure experiments have been classified as additive (equal to the sum of the effects of the individual pollutants), synergistic (greater than the additive effects), or antagonistic (less than the additive effects).

In 1966, Menser and Heggestad reported that tobacco plants suffered 25-38% leaf damage upon exposure to a combination of 240 ppb sulphur dioxide and 270 ppb ozone for two hours, whereas either pollutant alone at approximately the same concentrations and for the same time period caused no injury. The leaf injury caused by the combination of the two gases resembled typical ozone injury. This finding prompted an active research effort to more thoroughly determine the interactive effects and their importance to the protection of plants from ozone exposure.

Plants have been found to respond differently if the pollutant mixture regime is changed. For example, Tingey et al. (1973) found that injury on broccoli showed an additive response to a mixture of 250 ppb sulphur dioxide and 100 ppb ozone for four hours, whereas tobacco showed a synergistic response. However, if the regime was changed to 100 ppb sulphur dioxide and 100 ppb ozone for four hours, the reverse occurred, with broccoli showing a synergistic response, and tobacco an additive response.

Heagle and Johnston (1979) demonstrated another factor that must be considered in assessing multiple exposure data. They found that when soybeans were exposed to mixtures of ozone and sulphur dioxide, the response to the mixture (synergism vs. antagonism) was dependent on the concentration used. Synergistic responses were associated with low-level exposures, while antagonistic responses were documented at levels of exposure that caused more severe injury.

In another study, Runeckles and Palmer (1987) showed that sequential exposures to nitrogen dioxide and ozone could lead to different species-dependent adverse growth effects: synergistic in bean and antagonistic in radish and wheat.

Other factors that have been shown to influence the response to multiple exposures include the duration and timing of the exposure and the age and condition of the plants at the time of exposure (Mansfield & McCune, 1988).

As additional information concerning the complexity of the interpretation of multiple exposure data became apparent, research effort was aimed towards reducing the number of factorial components in the experimental technique. Ormrod et al. (1984) explored the concept of response surface techniques in studies with ozone and sulphur dioxide. This technique offers many benefits and may be further refined as work in this area progresses.

In preliminary experiments, Heck (1968a) reported that a mixture of three pollutants (nitrogen dioxide, sulphur dioxide and ozone), each at a concentration of 50 ppb, injured tobacco plants. Reinert and Gray (1981) reported that radish growth was a sensitive measure of the effects of the three pollutants in combination. Radish plants were exposed to either 200 or 400 ppb of the three pollutants alone or in combination for periods of either three or six hours. Nitrogen dioxide alone caused no visible injury, sulphur dioxide alone caused trace injury at 400 ppb for six hours, whereas ozone alone caused trace injury at 200 ppb for six hours. The exposure of radish plants to all three pollutants in combination caused greater than additive visible injury in comparison to the responses to individual pollutants or to any two-pollutant combination.

The foregoing results represent only a few of the experiments published on plant response to gaseous pollutant mixtures under short-duration, high-concentration dose regimes. Reinert (1984), Kohut (1985), Mansfield and McCune (1988), Wolfenden et al. (1992), Shriner et al. (1991), Torn et al. (1987), Ormrod et al. (1984) and Runeckles (1984) all present more comprehensive summaries and discussions of work conducted in this area over the past decade.

With increasing focus on acid rain and its precursors, and attempts to identify causal agents in a number of forest decline scenarios in the U.S. during the mid-1980s, there also was an increased emphasis on interactions involving tree seedling response to ozone, acid rain/fog, and sulphur and nitrogen oxides. Since it is not possible to thoroughly review all such efforts, the reader is directed to some of the individual studies in which these interactions were explored (Chappelka et al., 1988a, 1988b; Elliot et al., 1987; Reich et al., 1987, 1988; Stroo et al., 1988; Laurence et al., 1989; Chappelka & Chevone, 1986). As with the earlier crop research, the results of these and other multiple-exposure studies have yielded a wide range of interactions between the exposure treatments, with ozone effects being exacerbated (synergism) in many of the experiments. However, in several studies, no adverse effects or interactions were apparent. Because these studies were conducted under experimental conditions using seedling material, extrapolation or generalization to natural forest settings can not yet be made. Nevertheless, the work has focused attention on an important area since single-pollutant exposures in nature do not occur throughout the life of a tree or forest stand. The importance of this concept is underscored by the search for causality in the many forest declines that are occurring throughout areas where ozone and other regional air pollutants (sulphur and nitrogen oxides and acidic precipitation) co-exist at concentrations in the range of established threshold levels for the individual components. Clearly, until this uncertainty has been resolved, there can be no conclusive or quantitative statement regarding the magnitude of ozone impacts on forest systems.

In the area of crop yield effects, there has emerged a better understanding of the impact of ozone interactions with sulphur dioxide and acid rain/fog. In the mid-1980s, a number of seasonal crop exposures utilizing open-top chamber exposure methodologies were conducted (Takemoto et al., 1988; Kohut et al., 1987, 1988; Heggestad et al., 1986; Surano et al., 1987; Heagle et al., 1974, 1983; Temple et al., 1987; Kress et al., 1986; Reich & Amundson, 1984). In all cases, ozone in combination with sulphur dioxide and acid rain/fog at exposure levels similar to those encountered under field conditions remote from specific point sources have not resulted in enhanced yield loss above the additive individual pollutant effects. Although the field studies have not covered all crops for which ozone exposure information is available, the body of evidence appears to rule out significant interactive effects involving ozone and these major regional pollutants. However, the interaction of ozone and nitrogen oxides or the three- or four-way interaction of ozone, sulphur dioxide, nitrogen oxide and acid rain has not been specifically addressed in any of the field oriented, crop yield response research to date.

The most recent studies involving ozone interactions with other atmospheric components include the effects of carbon dioxide (climate change) and ultraviolet light (resulting from stratospheric ozone depletion). The results of these studies are still considered inconclusive in terms of interactions with ozone. A full summary of these findings can be found in Runeckles and Krupa (1994) and Krupa and Kickert (1989).

In summary, although photochemical oxidant and other co-occurring atmospheric pollution contains numerous constituents in addition to ozone, the limited amount of information available on their effects on vegetation precludes any specific estimate of the magnitude of their effects in relation to the effects of ozone alone. This finding should be considered in the light of information published by Lefohn and Tingey (1984) and Lefohn et al. (1987) who reviewed patterns of co-occurrence of ozone, SO_2, and NO_2 in urban, rural and remote sites in the U.S. during 1978-82. They found that co-occurrences were usually infrequent and of short duration. They also reported that the most frequent types of co-occurrence were usually sequential or a combination of sequential and overlapping exposures of short duration.

Because of its phytotoxic potential, PAN is undoubtedly the most important co-occurring pollutant and would not be expected to exhibit the short-duration type of co-occurrence pattern described above. However, although PAN has been documented as acting synergistically with ozone in causing increased foliar injury to some species under some conditions, this co-occurrence reaction cannot yet be generalized, as considerable variability has been demonstrated in the experimental findings published to date (synergistic, antagonistic and additive responses). Based on minimal data, that has shown relatively low PAN levels, there is insufficient information to provide a review of PAN/ozone exposure in the Canadian context.

8.1.5 Effects on Canadian Vegetation

Several studies have been designed in Canada to assess foliar injury response to ambient ozone:

- New Brunswick (Tims & Knight, 1987)
- Ontario (Pearson, 1989; Emerson, 1996)
- Quebec (Maltais & Archambault, 1985, 1986)
- British Columbia (Runeckles, 1989)

These programs have documented foliar injuries to a number of sensitive crops in New Brunswick (potato), Quebec (dry bean, soybean, tobacco), Ontario (dry bean, soybean, potato, tomato, onion, tobacco, cucumber, grape, peanut, radish) and British Columbia (pea, potato). Although these studies were not designed to determine the exposure threshold for foliar injury in all cases, injuries were observed in locations where hourly ozone levels exceeded the one-hour Canadian objective of 82 ppb for one or more hours prior to the investigation.

There have also been a number of Canadian investigations into the impact of ozone on crop yield. Using the concept of a seasonal mean as developed in the U.S. NCLAN studies as well as other U.S. and Ontario field exposure assessments via chemical protectants, Pearson (1989) determined the potential impacts (yield loss) of ozone exposure on Ontario vegetation. While the limitations of the seasonal mean exposure statistic were beginning to be recognized at that time, the lack of any generally accepted alternative index, or exposure function which could be used resulted in a decision to proceed with a seasonal mean approach. An analysis of the Ontario air quality data to assess the relationship between a seasonal mean and exceedances of an hourly criterion value of 80 ppb also was undertaken. Because the exposure-response analysis was not restricted to the utilization of field research results from the NCLAN program, and actually included many field studies conducted in Ontario for which seasonal means could be calculated, bias which would have resulted from equating crop responses to seasonal means derived from U.S. air quality data was likely reduced.

The value of increased productivity to 19 agricultural crops and ornamentals (turfgrass, Christmas trees and nursery stock) in Ontario was estimated at from 17 to 70 million dollars annually. The estimate was based on crop loss values determined from an analysis of the North American field research data (open-top chambers as well as chemical protectant studies) and subsequently adjusted downwards to reflect uncertainties in agricultural, geographical and experimental variables. The upper range represented approximately 4% of the total $1.9 billion in Ontario crop sales. Crops considered to be at greatest risk included: dry bean, potato, onion, hay, turnip, winter wheat, soybean, spinach, green bean, flue-cured tobacco, tomato and sweet corn. Crops marginally at risk (due mainly to insufficient data that did not permit more accurate quantification of loss) included cucumber, squash, pumpkin, melon, grape, burley tobacco and beet.

With the exception of Alberta (Torn et al., 1987) and British Columbia (Runeckles, 1989; Rafiq, 1989), this type of multi-crop impact analysis has not been conducted in other areas of Canada. In Alberta, the analysis consisted of a review of the available literature for ozone response based on crops grown. This information was then compared with a limited amount of urban ozone-monitoring data, and it was concluded that there were no identifiable risks to sensitive crops at that time. In British Columbia, processing peas and potato crops have been fumigated with ozone under field conditions to better define the exposure-response factors. In addition, a preliminary estimate of the crop loss due to ozone levels experienced in the lower Fraser Valley was undertaken in 1986 (Rafiq, 1989) and estimated losses at approximately $9 million. This estimate was based on a seasonal mean analysis similar to that done in Ontario (Linzon et al., 1984), but modified to reflect the longer growing seasons and milder temperatures than those in Ontario.

A brief description of the documented effects (foliar injury and yield loss) of ozone on some important field and horticultural crops in Canada follows. In many cases, this information has been compiled from visual assessment programs and chemical protectant studies conducted by various provincial agencies or research institutes. Where this information was not available from Canadian studies (either as open-top chamber studies, visual assessments or chemical protectant studies), the results of field exposure studies involving crops that normally are cultivated in Canada have been provided.

The main objective of this summary is to provide a real-world context to the impact of atmospheric ozone on ozone-sensitive crops grown in Canada and to serve as supporting evidence for the experimental findings from the U.S. and other countries that, of necessity, have been used in the exposure-response assessment. Familiarity with the symptoms affecting the various crops should also provide agencies and regulators with information to help assess the need for or effectiveness of oxidant control programs at a local or regional level.

Crops were included in the following alphabetically ordered list on the basis of investigative findings in the published literature and in internal government documents. As such, crops common to Canada but not appearing on this list should not be considered resistant to the impact of ozone—their response is simply not known at this time.

Bean, green/snap

Both acute and chronic ozone exposures of horticultural snap, bush or common beans as well as lima beans have been shown to cause foliar injury (Blum & Heck, 1980; Meredith et al., 1986). Many studies conducted under different environmental conditions, using different ozone concentrations and exposure durations, have also demonstrated the susceptibility of snap beans to ozone effects on dry matter accumulation, relative growth rate, pod production, nodulation and leaf nitrogen content. These studies are summarized in Blum and Heck (1980).

Studies of yield effects under field conditions using open-top chambers also have been conducted, although in many cases specific data on exposure parameters were not provided. In a five-year study in Maryland (1972-79), average yield reductions in non-filtered chambers relative to charcoal-filtered air chambers for snap beans ranged from 5-27% (Heggestad, 1980). Monitoring results for a nearby site in Maryland (Beltsville) were provided by Heggestad et al. (1980) and revealed that during the period from June through August, hourly ozone values equaled or exceeded 100 ppb on an average of 14 times per year. This frequency is similar to many sites in Canada.

In 1973, MacLean and Schneider (1976) detected a 26% yield loss for snap beans in unfiltered open-top chambers compared with similar plants grown in carbon filtered air. The average daily (06:00-21:00 EST) ozone concentration in the unfiltered chamber over the 43-day duration of the experiment was 41 ppb.

The most comprehensive field evaluation of ozone impact on common bean cultivars has been reported by Heck et al. (1988). In addition to the yield loss information, the authors concluded that the results provided strong support for the concept of predicting yield reduction under chronic ozone exposure (based on foliar screening results and that the NCLAN concept of comparing relative yield losses) may permit comparisons of results across seasons, years and cultivars, even though actual yields may vary greatly.

Bean, white/dry

In 1961, bronzing and rusting of white-bean foliage was reported throughout southwestern Ontario (Clark & Wensley, 1961), with yield losses in the most severely affected fields estimated at 45%. Following extensive field work in 1965 and 1967, the disorder was found to be associated with the occurrence of elevated levels of atmospheric ozone (Weaver & Jackson, 1968). The symptoms, first evident at some time between flowering and normal plant senescence, a critical period in the development of yield potential, appear as a bronze-coloured necrotic stipple on the foliage, resulting in rapid and premature leaf drop and reduced seed set as the symptoms become more severe.

The Ontario Ministry of Environment and Energy (MOEE) has conducted visual assessment surveys throughout the major production areas in southern and southwestern Ontario since 1971. Visual ratings of farm fields or experimental cultivar plantings have been made with injury severity ranging from trace (< 1%) to severe (> 35%) bronzing and associated premature foliar loss (Pearson, 1983, Emerson, 1996). These annual visual surveys have also confirmed that in any given year, the severity of bronzing symptoms was linked more with the phenological stage of the crop at the time of exposure to ozone than with varietal selection.

Experiments using chemical protectants have helped to provide information on yield losses related to the bronzing disorder in Ontario. In 1973, a 13% yield increase was associated with the reduction in bronzing severity (Curtis et al., 1975), while in 1976, yield increases of up to 36% (27% yield reduction) were realized (Hofstra et al., 1978). In 1977 and 1978 (Toivonen et al., 1982), white bean yield increases with antioxidant chemical protection were not as high (16 and 4%, respectively) and this was attributed to climatic factors (drought).

In other chemical protectant studies during 1977, 1978 and 1979 (Temple & Bisessar, 1979; Hucl & Beversdorf, 1982; Toivonen, 1980), significant yield losses were confirmed on numerous varieties across most of southwestern Ontario.

Beet

The impact of ozone on garden beet was demonstrated in a controlled exposure in California (Ogata & Maas, 1973). Ozone symptoms appeared as a fine stipple on the upper leaf surface of oldest leaves within two days of fumigation for two or three hours per day of ozone at 150 ppb. With continued exposure, the damaged areas expanded and red anthocyanin-like pigment in the interveinal areas turned a dark purple. In advanced stages, the interveinal areas became necrotic and desiccated. Significant reductions in storage root weight were recorded with exposure durations in excess of one hour per day. In a more recent California study (McCool et al., 1987), using closed-top field chambers with a 12-hour seasonal mean ozone statistic (9 ozone concentration regimes), yield reductions of 6.6 and 11.1% were calculated from a linear model for 12-hour seasonal means of 40 and 50 ppb, respectively.

Cucurbits (Cucumber, Squash, Melon, Pumpkin)

Chlorotic mottle of leaves, early leaf senescence, and possibly increased susceptibility to diseases are problems incurred by cucurbit species in southern Ontario each year due to oxidant exposure (Ormrod, 1980). In 1979 and 1980, studies were undertaken to assess the relationship between foliar symptom development and yield suppression in cucumber. The studies utilized a number of different locations using two different chemical protectants. The results (Ormrod, 1980, 1981) revealed that at some locations there was a cultivar response to chemical protection. The results in 1979 were less conclusive than those of 1980, when overall reductions of 13% were recorded, with one location (all cultivars) yielding 15% less in unprotected cucumber plots compared to those provided with antioxidant protection.

Studies on muskmelon and watermelon in Indiana also have confirmed the role of ozone in extensive foliar injury development and reduced fruit yield (Snyder et al., 1988; Eason et al., 1986). In open-top chambers with and without carbon filtration, significant yield reductions of

21.3 and 20.9% for marketable fruit weight and fruit number were documented for “Superstar” muskmelon (Snyder et al., 1988).

Grape

Dark brown to black spotting or stipple of grape leaves was first reported in California (Richards et al., 1958) and attributed to the presence of atmospheric ozone in the grape production areas. The symptoms, which include premature leaf senescence and abscission, are commonly called ‘brown leaf disorder’. These symptoms reportedly are widespread on several American cultivars and French hybrids grown in vineyards throughout upper New York state (Shaulis et al., 1972). In 1973 and 1974 (Kender & Carpenter, 1974), a large number of grape cultivars and hybrids in both New York state and Ontario was assessed for severity of oxidant injury.

These findings prompted a four-year Ontario study to ascertain the extent of the problem in terms of the severity of foliar injury development and potential adverse effects on crop yield and quality. These results (Ormrod, 1979) confirmed that the ‘brown-leaf’ disorder of grapes is a readily recognizable problem in Ontario each year. The failure of the antiozonant chemical treatment to provide sufficient protection from foliar injury development negated the efforts to quantify any adverse yield and quality effects. In California, however, adverse yield and quality effects were demonstrated, using Zinfandel grapes in field studies with protection by charcoal-filtered chambers (Thompson & Kats, 1970).

In a review of air pollution effects on grape vines, Weinstein (1984) summarized the available research and concluded that losses in fruit yield and quality can occur in the field at ambient ozone concentrations, with some cultivars exhibiting extreme susceptibility while others demonstrated remarkable tolerance. However, most observations have been associated with foliar lesions and the relationship between these symptoms and fruit yield has not been well established.

The work of Musselman et al. (1985) in New York, using the Concord cultivar with mature vines in open-top chambers, confirmed the conclusions drawn by Weinstein (1984). The exposure of the crop to ambient ozone in combination with different dose regimes of sulphur dioxide revealed that intermittent exposures of sulphur dioxide reduced foliar tolerance of ozone. There were no significant effects, however, of one or two years of ambient air filtration (ozone reduction) on vine yield, growth, maturity or soluble fruit solids.

Hay

Compared with annual crops, relatively little information is available on multi-year yield responses of perennial forage crops to ozone (Temple et al., 1988).

Under controlled environmental conditions, Brennan et al. (1969) evaluated the foliar response of numerous forage legumes and found that sensitivity increased in the following order: crown vetch > alfalfa > alsike clover > white sweet clover > red clover.

In the case of clover, ozone has been shown to reduce the yield, inhibit nitrogen fixation, shift the grass/clover yield ratio in favour of the grass and accelerate the loss of clover from the combination (Blum et al., 1983). In another study, Blum et al. (1982) also reported that ozone suppressed root growth and reduced total non-structural carbohydrate reserves in roots and shoots of clover. Other studies involving the exposure of clover to ozone are summarized in reviews by Ensing and Hofstra (1982), Kochhar et al. (1980) and Bennett and Runeckles (1977).

In California, Middleton et al. (1950) estimated that 15% of the alfalfa crop was lost due to air pollution exposure in 1949. Oshima et al. (1976) also used alfalfa in California to assess the impact of ozone via controlled, containerized studies across an ozone gradient. Other studies that review the impact of ozone on alfalfa include Cooley and Manning (1988) and Olszyk et al. (1986, 1988).

Onion

Onion leaf dieback and flecking have been attributed to a number of parasitic and non-parasitic agents since the first report of the disorder in Wisconsin in 1903 (Whetzel, 1904). Subsequently, the search for the causal agent in the tip-burn or blast syndrome centred on atmospheric ozone. Engle et al. (1965) found a close relationship existed between the presence of flecking and tip-burn in onions and high levels of ozone. Engle and Gabelman (1966) later published on the genetic resistance of certain cultivars of onions to ozone exposure.

In Ontario, Wukasch and Hofstra (1977a, 1977b) examined the effects of ozone exclusion and chemical protection on the yields of field-grown onions. They documented a 28% yield reduction in non-filtered compared with charcoal filtered chambers, and a 22% yield reduction in control plants (Autumn Spice) compared with those provided with an antiozonant protectant. Another cultivar (Rocket) failed to confirm these significant protectant effects.

In a later California study, using closed-top field fumigation chambers, McCool et al. (1987) demonstrated a significant yield loss for green bunching onions exposed to various 12-hour seasonal mean ozone concentrations. The linear response model predicted yield losses of 14.9% and 24.8% for seasonal means of 0.04 and 0.05 ppm ozone using the 12-hour seasonal mean statistic.

Potato

The foliar symptoms referred to as ‘speckle leaf’ on this crop usually appear after mid-July when the plant has flowered and the tubers are developing. As the demands for photosynthetically produced nutrition at this time are at their peak, the potential for adverse yield effects is considerable. The symptoms appear either as a blackened stipple or flecking on the upper leaf surface which can coalesce and become bifacial necrotic lesions; or as undersurface, irregularly sized, silver-grey lesions, which also can become bifacial as they increase in size and severity. Adding to the total impact of this injury are findings (Bisessar, 1982; Holley et al., 1985) which demonstrate that ozone injury predisposes the plants to attack by the early blight disease organism, thereby necessitating additional disease control treatments.

In Ontario, ozone induced foliar symptoms were observed as early as 1954 (Johnson, 1972) and in later years (McKeen et al., 1973). On the basis of yield assessment studies conducted in Ontario and in northeastern U.S., yield losses and tuber quality effects have been documented on several of the most sensitive processing cultivars. In Ontario, Ministry of Energy and Environment (MOEE) also has conducted annual foliar injury assessment surveys throughout the major potato production areas since 1977 and in that time have examined over 600 plantings and recorded foliar injury development ranging from less than 1 to 30% leaf area (Pearson, 1983; Emerson, 1996). Foliar injuries have also been reported in New Brunswick and British Columbia.

In studies using antioxidant protective chemicals, potato (Norchip) yield losses in Ontario with and without disease control were 24.2% and 26.2%, respectively (Bisessar, 1982). An average, significant yield loss of 8.2% in an ozone sensitive cultivar (Norchip) also was reported during a three-year trial in Ontario (Holley et al., 1985). This loss could be attributed to ozone effects that were apparent under a disease control program; no demonstrated yield effects were detected with two other, more ozone resistant cultivars (Chieftan and Kennebec) in the same trial (Holley et al., 1985). The trials, which used chemical protectants, are comparable to open-top chamber studies undertaken in 1986 (Pell et al., 1988). Pell et al. (1988) also demonstrated significant tuber quality effects. Another open-top chamber study conducted earlier in California (Foster et al., 1983) confirmed a linear exposure-response to season-long ozone exposures in terms of tuber number and total tuber yield. Runeckles et al. (1990) observed a response similar to that found by Foster et al. (1983) as a result of season-long exposures to ozone in an open-air field fumigation system.

On the basis of these studies as well as general reports of foliar injury and/or yield losses in northeastern and southwestern U.S. (Mosley et al., 1978; Hooker et al., 1973; Foster et al., 1983) and a documented 50% loss to a sensitive variety under greenhouse conditions (Heggestad, 1976), there is convincing evidence that this crop is reduced in yield by ozone exposure scenarios similar to those experienced in several parts of Canada. An assessment of potato yields from 1941-94 throughout Ontario (McKeown, 1996) has demonstrated that yields which had been increasing until the early 1960s then leveled off and began to decline in the 1970s. Potato experts are concerned that this trend is occurring despite newer varieties, better pest control, extra fertilizer, irrigation and soil fumigation.

Soybean

In the early 1970s, some greenhouse studies documented the foliar response of a number of soybean cultivars to acute and chronic doses of ozone (Heagle, 1979; Howell & Kremer, 1972; Tingey et al., 1972). It was later demonstrated (Heagle & Letchworth, 1982) that neither foliar injury nor the vegetative shoot weight response of cultivars to ozone allowed reasonable prediction of cultivar yield response. At the end of the decade, studies confirmed crop yield losses under field conditions using open-top field chambers equipped with ozone filtration devices (Heagle & Heck, 1980; Kohut et al., 1977). These studies underscored the need for more accurate assessments of yield effects utilizing open-top chambers with supplemental ozone additions (Kress & Miller, 1983). During this period of active NCLAN supported and independent research, a number of investigations employing a variety of potentially interactive variables—sulphur dioxide, acid rain, soil moisture—were conducted.

With the exception of the chemical protectant studies (Smith et al., 1987; Brennan et al., 1987) and an earlier open-top chamber study (Howell et al., 1979), the experimental yield losses from the various controlled exposure studies (Kohut et al., 1986; Reich and Amundson, 1984; Heagle et al., 1986, 1987b) revealed a fairly uniform degree of plant response, considering the potential influences of location, exposure dynamics, cultivar, soil moisture and other environmental variables.

Because of its ozone sensitivity and importance to U.S. agriculture, soybean has been the primary focus in the experimental study of ozone-soil moisture interactions and the development of predictive moisture stress models for crop loss assessment (Heggestad et al., 1985, 1988; Heagle et al., 1987; King et al., 1988; King & Nelson, 1987). On the basis of this work, King and Nelson (1987) predicted a 23% decline in sensitivity of drought-stressed plants to ozone based on a 1980 U.S. ozone exposure scenario. For the period 1979-83, the mean predicted ozone impact on soybean yield was 19% less when the plants were under moisture stress, than was predicted for adequately watered soybean-yield.

Spinach

Several studies have documented the impact of ozone on spinach plantings (Daines et al., 1960; Manning et al., 1972) and confirmed cultivar response variability and typical short-term acute foliar symptoms. Heagle et al. (1979a) reported on the first growing season exposures, conducted in 1976, to determine whether spinach cultivars vary in sensitivity and to establish threshold doses of ozone for injury and decreased shoot weight. The authors confirmed that under seasonal exposure regimes, the foliar symptoms resembled those described for acute exposures; however, the major symptom was chlorosis, as opposed to bifacial necrosis. There were no relationships between foliar injury and shoot fresh or dry weight.

Sweet corn

In the first report ever to demonstrate yield loss in an agronomic crop exposed to long-term, low levels of ozone under field conditions using field exposure chambers, Heagle et al. (1972) evaluated the response of two cultivars of sweet corn (Golden Midget and White Midget). Ozone injury was described as small white or tan adaxial necrotic spots plus early chlorosis and senescence on the lower leaves. Growth reductions were not proportional to injury severity.

In California, Thompson et al. (1976) used open-top field chambers with and without carbon filtration and demonstrated foliar symptoms similar to those reported in other studies. Both cultivars (Monarch Advance and Bonanza) were seriously injured in ambient air; however, growth and yield parameters were more significant for Monarch Advance, with the greatest response being an effect on number and quality of seeds set on primary ears.

Tobacco, burley

Weather fleck of tobacco, so named because of its relationship to certain weather conditions, has been recognized as an ozone induced foliar disorder in Ontario since 1954 (Cole & Katz, 1966). Weather fleck has also been recognized as a factor in the production of tobacco in Quebec (Maltais & Archambault, 1985, 1986). The symptoms appear on newly expanded leaves, the younger and older leaves being more resistant. Symptoms normally first appear on the upper leaf surface as greyish, water-soaked lesions that become light ivory to tan-brown in colour with time. In more severe episodes the lesions can coalesce into larger flecks or spots and become bifacial with increasing severity. Successive episodes of ozone fumigation result in new lesions appearing on healthy tissues of recently injured leaves as well as newly expanded leaves higher on the main stem.

Weather fleck results in moderate damage to the burley tobacco crop in southwestern Ontario each year (Anderson & Welacky, 1983). The loss is attributed to the shattering of flecked leaves during curing and stripping operations. There is also potential for adverse effects on quality since chemical characteristics are affected (Huang et al., 1976; Menser et al., 1977). In 1980 and 1981, visual estimates of weather fleck damage on 13 burley cultivars at Harrow, Ontario, revealed mean damage on leaves 1-12 ranging from 3.0 to 7.2% in 1980 and 0.2 to 9.4% in 1981 (Anderson & Welacky, 1983).

Tobacco, flue-cured

Although considerable success has been achieved in breeding ozone resistance into commercially acceptable tobacco cultivars, yield losses associated with this crop continue to affect tobacco production (Ormrod et al., 1980; Watson & Sheidow, 1982). In 1972 and 1973, Gayed and Watson (1975) estimated decreased leaf weight and quality effects of 0.73% while estimates of tobacco crop loss in Ontario for the years 1975-81 varied from 0.2-2.5% (Watson and Sheidow, 1982). An MOEE visual assessment of foliar injury severity consisting of 33 separate observations throughout the major tobacco production areas of southern Ontario in 1977 confirmed the presence of foliar injury development ranging from < 1 to 20% on flue-cured tobacco species (Pearson, 1983).

Tomato

Tomato is an ozone sensitive crop species and has been investigated for cultivar sensitivity (based on foliar injury) by a number of researchers. Typical injury symptoms are frequently reported in the field in Ontario (Pearson, 1983).

There are numerous reports which document the adverse effect on tomato yield due to ambient (MacLean & Schneider, 1976; Oshima et al., 1977; Heggestad et al., 1986; Heck et al., 1984b) or controlled environment exposure (Henderson & Reinert, 1979). In North Carolina, early marketable yield of some tomato cultivars was significantly reduced by exposure of the plants to ozone prior to their establishment in the field (Henderson & Reinert, 1979). In spite of the fact that the final total yield was not affected, an economic loss was predicted based on the price differential between the early- and late-season markets. In a New York study, MacLean and Schneider (1976) documented a 33.7% yield reduction effect for plants grown in unfiltered chambers relative to charcoal-filtered chambers. The calculated average seven-hour seasonal mean in the filtered chamber over the duration of this experiment was 22 ppb ozone while that in the unfiltered chamber was 63 ppb.

As part of the NCLAN study, yield loss with Murrieta tomato in California (Surano et al., 1987) was estimated at 2.4 and 7.5% for seasonal seven-hour exposures of 40 ppb in 1981 and 1982, respectively, and 4.9 and 14.4% at 50 ppb in 1981 and 1982, respectively. Heggestad et al. (1986) reported a 16.3% yield loss for Jet Star using filtered versus unfiltered open-top field chambers in Beltsville with a calculated seven-hour seasonal mean of 50 ppb compared to 15 ppb in filtered chambers.

There are two Ontario reports citing an adverse effect of ozone on tomato yield. Legassicke and Ormrod (1981) record a yield reduction of 23.7% for one cultivar compared with tomato plants afforded chemical protection. Ormrod (1983) found reductions in tomato yield for several cultivars at several locations in both 1980 and 1981. Although many of the cultivar comparisons were not statistically significant, there were some that approached 30% yield reduction.

Turnip

Significant yield losses have been documented for this crop. At Raleigh, foliar injury appeared as chlorosis on cotyledons followed by chlorosis of a few of the oldest true leaves. After one 3.5-hour acute episode during late November, there were water-soaking symptoms apparent on expanded leaves of all cultivars (Heagle et al., 1985).

A California study (McCool et al., 1987) conducted under significantly different climatic conditions using closed-top field chambers and a 12-hour seasonal ozone exposure duration, obtained yield response very similar to that in Raleigh.

Winter wheat

Until recently, little was known about the impact of season-long ozone exposure on the yield of winter wheat. The work of Shannon and Mulchi (1974) and Sechler and Davis (1964) had indicated that wheat was sensitive to short-term acute exposures at anthesis under controlled-environment and greenhouse conditions and that, to a limited extent, cultivar differences were apparent. In 1978 and 1979, Mulchi et al. (1986) conducted field experiments in Maryland using open-top chambers and six cultivars of soft red winter wheat. Although the ozone exposure was not expressed in a seasonal format, all six cultivars exhibited susceptibility to ozone injury during anthesis. In an earlier field experiment (Phillips & Runeckles, 1974), wheat biomass was reduced with exposure to five-hour-per-day concentrations ranging from 80 to 100 ppb. Yields were not reported.

In later NCLAN studies (Kress et al., 1985; Kohut et al., 1987) utilizing both constant and proportional ozone exposures, significant yield losses were recorded for both soft and hard winter wheat cultivars. In the latter study, ozone was shown to accelerate senescence of flag leaves and heads, with reductions in yield being highly correlated with reductions in net photosynthesis (Amundson et al., 1987).

Crops with limited experimental results

Foliar injury and yield loss have been documented for a number of other crops grown in Canada, including: radish, pea, carrot, celery, cabbage, cauliflower, eggplant, pepper, sunflower, peanut, field corn, strawberry, spring barley, oats and apple. In the case of celery, pepper, strawberry, spring barley, field corn and leaf lettuce, studies have used either open- or closed-top chambers with constant or proportional ozone dispensing under field conditions (Takemoto et al., 1988; Temple et al., 1985; Heagle et al., 1979b; Kress & Miller, 1985; McCool et al., 1987). Runeckles et al. (1990) reported yield losses of processing peas as a result of season-long exposures in an open-air field fumigation system.

Sensitivity to ozone also has been demonstrated for the other crops; however, except for peanut (Ensing et al., 1985), the experimental studies have been limited to short-duration, foliar-effect or biomass evaluations which do not permit an assessment of yield impact under field conditions. The peanut study in Ontario did document an adverse impact on yield, but this was limited to one of several cultivars tested using chemical protectants.

Forest Trees and Unmanaged Vegetation

Ozone concentrations are elevated in forest areas within portions of four Canadian terrestrial ecozones: Atlantic Maritime (New Brunswick, Nova Scotia, Prince Edward Island), Mixedwood Plain (southern Quebec, southern Ontario), Pacific Maritime (Lower Fraser Valley, British Columbia) and, to a lesser extent, the Boreal Shield (southwestern Ontario). In these areas, ozone concentrations exceeded the current NAAQO of 82 ppb for between 10 to 50 hours per year during 1986-93 (Environment Canada, 1996).

In Ontario, foliar symptoms associated with ozone injury to white ash and eastern white pine have been observed by MOEE staff. Reductions in radial growth of a number of hardwood species also have been documented throughout these areas (MOE, 1989). However, until such time as additional studies are undertaken, the role of ozone in these documented forest growth reductions cannot be confirmed or quantified.

On the east coast along the 600-km Bay of Fundy-Gulf of Maine transect, declines of white birches and red spruce occurred in the 1980s. This area receives some of the most acidic fogs and has recorded among the highest hourly ozone concentrations in North America, with the exception of southern California (Jagels, 1986). Although ozone may have been an important interacting factor (Cox, Spavold-Tims & Hughes, 1989), foliar injury to birches (Cox, Lemieux & Lodin, 1996) and changes to red-spruce needle-surface properties (Percy et al., 1993) were related directly to fog frequency and chemistry. Field observations on declining red spruce trees confirmed or were later supported by ozone and acid fog experimental exposures using red spruce seedlings (Percy et al., 1990; Percy et al., 1992) or recrystallized needle waxes (Percy et al., 1992).

8.2 QUANTITATIVE TOXICITY ASSESSMENT

8.2.1 Experimental Methodology to Assess Crop Response

With the recognition in the late 1970s and early 1980s that foliar injury resulting from short-term, acute fumigations may not adequately characterize the season-long, chronic effects of ozone exposure on crop and forest yield or biomass production, a number of techniques have been developed to facilitate a more accurate, quantitative assessment of ozone impacts under conditions more typical of field exposure. A review of the various approaches to experimental field exposures in examining ozone-induced crop loss is summarized in Table 8.2. A detailed description of the individual exposure methods can be found in Hogsett et al. (1987a, 1987b).

Among all field exposure methods, the open-top chamber approach has been the most frequently used and accordingly has formed the basis for the exposure-response assessment summary that has been undertaken in this document. This section, essentially extracted from Manning and Krupa (1992), provides additional detail on the open-top chamber methodology.

In response to the observed excessive increase in daytime temperature and the lack of exposure to ambient rainfall in closed field chambers, Heagle et al. (1973) and Mandl et al. (1973) developed large cylindrical open-top chambers (OTCs). Charcoal- or dust-filtered ambient air is blown into the bottom of the OTC at a velocity that permits it to rise within the chamber and exit through the open top. This reduces ingress of ambient air from above the OTC and prevents problems with daytime increases in temperature. In addition, ambient rainfall enters through the open top. The Heagle OTC design (Heagle et al., 1973) has been the one most frequently used for more than 20 years, including the U.S. Environmental Protection Agency’s National Crop Loss Assessment Network (NCLAN) (Heck et al., 1982, 1984a, 1984b, 1988; Heagle et al., 1988). Similar OTCs have been used to study ozone effects on plants as diverse as cereals, grapevines and large trees. Design variations in OTCs have been described in detail by Hogsett et al. (1987a, 1987b) and Last (1986). With the addition of a rain cap, OTCs can also be used to study precipitation effects and soil moisture regime interactions (Hogsett et al., 1985).

Table 8.2 Summary of field exposure systems used to assess ozone effects on crops.

Systems	References
Open-air plumes [Circular, grid, linear, square, zonal air pollution system (ZAPS)]	Lee and Lewis (1978), Greenwood et al. (1982), Thompson et al. (1984), McLeod et al. (1985), Runeckles et al.(1990).
Air pollutant exclusion	Jones et al. (1977), Shinn et al. (1977), Olszyk et al. (1986a, 1986b).
Linear gradients	Shinn et al. (1977), Laurence et al. (1982), Reich et al. (1982), Olszyk et al. (1986a, 1986b)
Field chambers Closed chambers	Roberts (1981), Ashenden et al. (1982), Musselman et al. (1986)
Down-draft chambers	Runeckles et al. (1978)
Open-top chambers	Mandl et al. (1973), Heagle et al. (1973, 1979), Nystrom et al. (1982)

Source: Modified from Manning and Krupa, 1992

Under conditions of low wind velocity, the charcoal filters may remove 50-60% of the ambient ozone. Downdraft incursions of ambient air into the OTCs increase with wind velocity, potentially causing problems in meeting specified treatment levels. Several designs involving additions of a baffle or frustum to the top portion of the OTCs have been evaluated to reduce downdrafts (Kats et al., 1976; Kohut et al., 1978; Davis & Rogers, 1980; Buckenham et al., 1981). The use of a truncated, cone-shaped frustum (Kohut et al., 1978) increases the removal efficiency of ambient ozone to 75% (Davis & Rogers, 1980). However, the advantages gained in ambient air exclusion are off-set by reductions in the ingress of ambient rain and solar radiation. However, the uniformity of distribution of introduced ozone within the OTC is increased (Davis & Rogers, 1980).

OTCs have been used for many years, allowing the accumulation of considerable information about their performance under a variety of conditions. Some advantages and disadvantages of the use of OTCs are summarized in Table 8.3. More extensive consideration of OTCs has been provided elsewhere (Krupa, 1984; Unsworth et al., 1984a, 1984b; Hogsett et al., 1987a, 1987b; Heagle et al., 1988; Ormrod et al., 1988; Heagle, 1989; Krupa and Nosal, 1989a).

OTCs were originally used to compare crop responses to CF (charcoal filtration) and NF (non-filtered, i.e., particle and dust filtration only) treatment under field conditions (Heagle, 1989). CF treatments were intended to remove ozone from the air in the OTC, while NF treatments were controls. CF was found to increase yields of crops such as bean, cotton, field corn, peanut, potato, soybean and wheat when comparisons were made with yields from NF. This allowed determination of possible ambient ozone effects on crops in any given area. Results varied from year to year as weather conditions and ambient ozone concentrations and exposure patterns varied.

Table 8.3 Advantages and disadvantages in the use of open-top chambers

Advantages	**Disadvantages**
Widely used with 15+ years of historical records, especially for CF/NF comparisons	Problems with comparison of results from CF, NF and AA
Crops can be grown to maturity in the field	Limited space in chambers; long-term use may mask effects in perennial plants and trees
Exposure-response studies at concentrations above ambient can be made by ozone additions	Microclimate effects may affect results (e.g., soil moisture problems, changes in insect and disease incidence)
Each OTC is cost effective, portable and durable	The many OTCs required for field work are expensive and labour-intensive; each chamber requires a 20-amp circuit
	Use leads to increased plant growth in cool seasons and winter compared to AA plants

Source: Manning and Krupa, 1992

Proportional or fixed concentrations of ozone, separately or in combination with other pollutants can be added to OTCs. This allows exposure-response studies in the field, with a range of concentrations of ozone above ambient levels (Heagle & Philbeck, 1979; Heagle et al., 1979; Heagle, 1989). Hogsett et al. (1987a, 1987b) and Nystrom et al. (1982) developed computerized systems to maintain OTCs and dispense ozone in a pattern that simulated fluctuating ambient air concentrations. Data from OTC exposure-response studies have been used to predict how changes in future, elevated ozone concentrations will affect crop yields.

Chamber effects have been intensively investigated and described in detail by Musselman et al. (1978), Olszyk et al. (1980, 1989), Weinstock et al. (1982), Ashmore et al. (1988), Colls et al. (1988), Heagle et al. (1988), Manning and Keane (1988), and Heagle (1989). A condensed summary of chamber effects, based on all of the previously cited work, is presented in Tables 8.4 and 8.5.

Howell et al. (1974) expanded the CF versus NF experimental approach to include comparisons with a comparably sized, non-enclosed ambient air (AA) or chamberless plot. Results from CF, NF and AA are not be directly comparable due to the composition of the air that plants are exposed to as a result of CF, particle (dust) filtration (NF), ambient air (AA), chamber and no chamber. An important consideration in such analyses involves an understanding of the type of charcoal used for filtration. Different types of charcoal provide different degrees of filtration of different pollutants. Nystrom et al. (1982) have used this feature to advantage in their differential studies on ozone, SO_2 and ozone + SO_2. Most recently, Olszyk et al. (1989) examined air composition in CF and NF and AA in the South Coast Air Basin in California and compared the efficiency of charcoal and particle filters. Concentrations of NO in CF were higher than in NF and AA, probably due to conversion of NO_2 to NO on the charcoal filter. Concentrations of ozone, NO_2, PAN, NO_3, S_2O_4, and NH_4+ were greatly reduced by charcoal filtration. To the contrary, plants in NF were exposed to near-ambient concentrations of ozone, NO_2 and PAN.

OTCs are useful in assessing ambient ozone effects on crops and simulating ambient effects, using comparisons between CF and NF as long as sufficient numbers of replicate chambers are used to provide adequate power for the statistical comparisons that are planned (Rawlings et al., 1988). Exposure-response studies with elevated ozone concentrations added to CF and NF can also be accomplished with OTCs. However, problems may develop when comparisons are made among CF, NF and AA. Chamber effects should always be investigated in a systematic way in order to determine their influence on plant responses in the CF and NF chambers. It is apparent that at a minimum, this analysis should include an assessment of differences in results between NF and AA.

Table 8.4 Effects of open-top chambers—physical changes

Physical parameters	Changes observed
Air filtration effect	
Activated charcoal (CF)	50-75% reduction in ambient ozone, increase in NO over ambient, and considerable reductions in NO_2, PAN, and SO_2
Particles (dust) (NF)	5-10% reduction in ambient ozone, some reduction in SO_2
Gas Exchange	
Canopy resistance	Similar to ambient air
CO_2 uptake	Inconsistent effects
Leaf boundary layer resistance	Less in OTCs
Stomatal conductance	Variable
Microclimate	
Air turbulence	Greater in downwind half of chamber
(due to ingress of ambient air)	
Dewpoint	0.5-2.0°C higher.
Light	Decrease of 12-20%, especially with dirty plastic, sun shadows possible
Relative humidity	5-10% increase or decrease
Temperatures	
Air	2.0-3.7°C increase
Leaf	Slight increase
Wind speed	Decrease

Source: Manning and Krupa, 1992

Table 8.5 Effects of open-top chambers—biological changes

Biological factors	Changes observed
Microclimate effects (not defined)	Plants in NF may yield less than in AA Plants in NF are often taller than in AA Chambers can delay leaf senescence and shorten maturity in grapevines
Pesticide usage (usually increased)	Unusually low occurrences of disease, insects and mites
Pollination problems	Fewer bees in chambers reduces seed pod set and seed yields in broad beans
Position effects in chambers	Higher yields may occur in northern rather than southern half of chambers

Source: Manning and Krupa, 1992

8.2.2 Form of an Exposure Index for Chronic Effects

One of the critical issues facing modellers of ozone exposure-plant response relationships is to understand how ambient concentrations of ozone are experienced by the plant. In other words, how does the dose taken up by the plant relate to ambient concentrations, and what factors and meteorological conditions are critical in determining the dose? These considerations have led to the separation of the concept of dose into the terms ‘exposure dose’ (Krupa & Kickert, 1987a) and ‘effective dose’ (Runeckles, 1974). ‘Exposure dose’ may be defined as the air concentration and exposure duration to which the plant is subjected. ‘Effective dose’ may be defined as the actual concentration over time absorbed by the plant. While most current ozone effects models use a numerical expression of exposure dose, the evaluation and use of the effective dose is a very important future need, particularly in terms of predicting the magnitude of plant response from a given set of air quality data. Runeckles (1992) provides a thorough discussion of ‘effective dose’.

A logical follow-up to the discussion above is a review of some concepts relevant to ambient ozone exposure dynamics and plant response. In a Weibull distribution of ambient ozone concentrations, the left portion of the distribution represents background ozone concentrations while the right portion of the distribution tail represents the occurrences of ozone episodes. While the occurrence of ozone episodes may be viewed as periods of stress, depending on the tolerance capacity of the plant and the nature of the other prevalent environmental conditions, periods of non-ozone episode days should be viewed as opportunities for repair or compensatory growth for the plant, providing that other conditions (i.e. water, light, nutrition) are favourable (see section 8.1).

Repair and compensation in response to low concentrations of ozone is largely a conceptual model based on a limited understanding of plant energy budgets. It is known that enzyme systems responsible for detoxifying oxidant species in cells require energy to function. As well, reactions between oxidant species and photosynthetic enzymes will reduce the amount of carbohydrates available for mitochondrial energy production, as well as for structural growth components. In an energy budget with no elasticity, either of these diversions of energy would be expected to reduce plant growth or yield. However, it is well accepted that energy budgets are elastic and plants may reallocate resources among various sinks to compensate for stress effects on a particular sink. Minor reallocations in response to low levels of stress may be accommodated within the elasticity of the plant, with no net effect to the plant or at least not of a magnitude that can be detected. Larger reallocations in response to greater stress may ensure survival, but with some net loss which is detectable. Depending on concentration and duration of exposure, the effect on the plant could be a negligible, minor or major reallocation of energy among plant parts or sinks. It is important to note that the concepts of repair/respite/compensation are not yet quantified, nor have the benefits of various characteristics of respite time been satisfactorily addressed, hindering the ability to model plant responses.

In recent years, one of the most frequently used terms in defining ozone exposure-crop and response relationships is ‘exposure index or indices’ (Heck et al., 1988). The concept of ‘dose’ forms the basis for the use of an exposure index or indices. The objective is to identify one or more ozone exposure parameters that can satisfactorily explain cause-effect relationships. The exposure index or indices also must demonstrate a generality and a universal applicability (Lefohn et al., 1989) and serve both as an assessment and predictive tool.

The relative importance of peak vs. mid-level ozone concentrations

According to Lefohn (1994), in a review of ozone exposure indices, the establishment of an ozone exposure index to predict vegetation response to ozone should consider the following:

- higher hourly average concentrations should be given more weight than the lower values and concentration is more important than duration in predicting vegetation effects (U.S. EPA, 1986, 1992; Hogsett et al., 1988; Lefohn, 1992);
- an index may attempt to protect vegetation from a) injury (measurable responses that do not influence agronomic yield or reproduction) or b) damage (all effects that reduce the intended human use or the value of the plant or ecosystem) (Tingey et al.,1990);
- hourly concentrations ≥0.10 ppm in the exposure regimes for most of the 22 NCLAN experiments resulted in a 20% yield reduction (Lefohn & Foley, 1992); Guderian et al. (1985) also noted the importance of hourly average concentration of ≥0.10 ppm in predicting plant response.

A number of investigators have used statistical regression techniques to identify numerical descriptors of ozone exposure that may best explain/predict crop response (Lee et al., 1988;

Lefohn et al., 1988; Tingey et al., 1989; Musselman et al., 1988, Hogsett et al., 1988, 1995). The coefficient of determination (R^2) and the residual mean sum of squares (RMSS) in the regression between various air quality indices and plant response have been used as criteria for evaluating the comparative efficacy of various exposure indices in establishing ozone exposure-crop response relationships

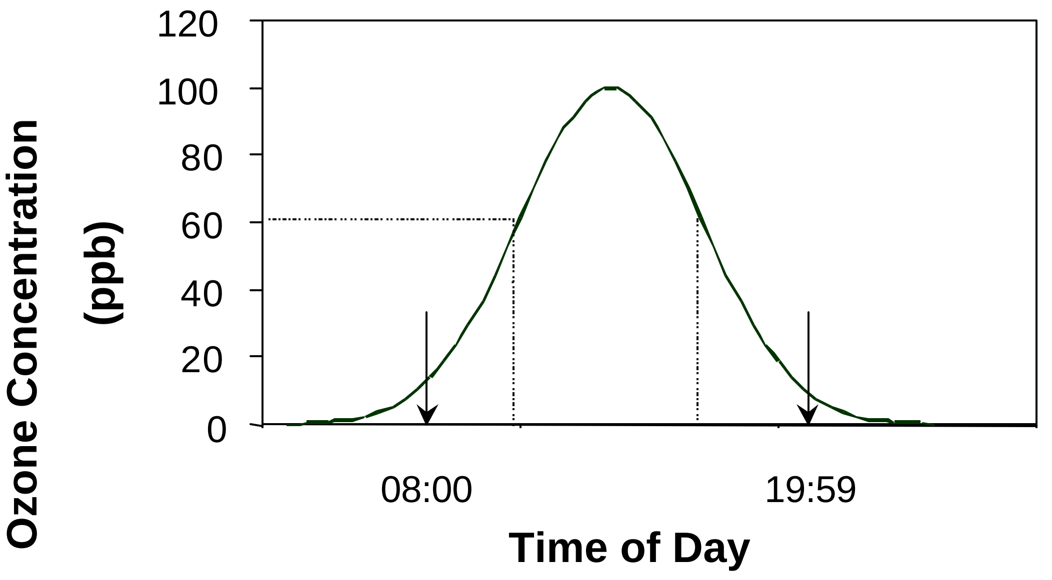
Based on the evaluation of over 500 different forms for a crop response index of ozone air quality, the findings of several scientists were summarized by Lee et al. (1988). This analysis pointed to the following factors as major considerations in the development of exposure indices:

- peak concentrations are more important than low concentrations in determining plant response;
- temporal distribution and intensity of concentrations over the exposure period need to be included;
- changes in exposure structure alter the magnitude of response;
- ozone effects increase with increasing duration of the exposure period although the exposure-response relationships are rarely linear;
- exposure cannot be characterized as the product of concentration and time since the effect of ozone on crop yield depends on the cumulative impact of high concentrations during the growing season
- plant sensitivity is not constant, but varies according to stage of development;
- time of increased plant sensitivity is species-specific, but generally occurs at or near maximum leaf expansion.

Considering these and other related ozone index development efforts, the authors concluded that the effects of ozone are cumulative and that higher concentrations are more important than lower concentrations in determining plant response. Accordingly, they believed that the form of a standard to protect vegetation should be cumulative (summation of hourly values) and should emphasize peak concentrations.

Two forms of exposure indices that performed the best in terms of statistical relationships with crop yield were the SUM60 and the sigmoidally weighted indices. The SUM60 index is calculated by summing hourly ozone when concentrations are equal to or greater than 60 ppb over a specified time period, usually during daylight hours (Figure 8.1). The index sometimes is referred to as the SUM06, which is identical to the SUM60 index except that units of ppm are used. The sigmoidal index is an exposure parameter that uses continuous concentration weighting between 0 and 1. Therefore, all concentrations are (nominally) included in the index, but they are weighted differently (with higher concentrations weighted more heavily that lower concentrations). Lee et al. (1988) noted that the sigmoidal type of concentration-weighted cumulative index did not involve the selection of an arbitrary discrete threshold concentration (as opposed to the selection of 60 ppb in the SUM60 index) which, from a biological perspective, could vary from species to species and from one stage of development to another.

Figure 8.1: SUM60 - A Cumulative Exposure Index



More recently, Lefohn (1994) has summarized some of the different types of indices that have been evaluated (but not including the sigmoidal indices) (Table 8.6).

Table 8.6 Summary of some ozone exposure-plant response indices

Index type	Index description
One event	The second highest daily maximum 1-h concentration (HDM2)
	The maximum of 7-h (P7) and 1-h (P1) maximum daily averages
	90th (PER90), 95th (PER95) and 99th (PER99) percentiles of hourly distribution
Mean	The seasonal mean of 7-h daily means (M7)
	The seasonal mean of 1-h daily peaks (M1)
	The effect mean (EFFMEAN) (Larsen and Heck, 1984)
Cumulative	The seasonal sum of hourly concentrations (TOTDOSE) or (SUM00)
	The seasonal sum of hourly concentrations at or above 0.06 ppm (SUM06), 0.07 ppm (SUM07), 0.08 ppm (SUM08), 0.10 ppm (SUM10)
	sum of hourly (08:00-19:59) concentrations at or above 60 ppb (SUM60)
	The seasonal censored sum of hourly concentrations at or above 0.08 ppm (AOT08) or 0.010 ppm (AOT10
	censored sum of hourly (07:00-21:00)concentrations at or above 40 ppb (AOT40)
	The total impact (TIMPACT) (Larsen et al., 1983)
	The ALLOMETRIC, in which the hourly concentration was weighted by raising to a power and summed (see Lee et al., 1989; Lefohn et al., 1988)
	Total hours with concentrations at or above 0.08 ppm (HRS08), or 0.10 ppm HRS10)
	The number of episodes (defined as an event with hourly concentrations above a threshold level) above a threshold of 0.08 ppm (NUMEP08), or 0.10 ppm (NUMEP10)
	The average episode length with threshold 0.08 ppm (AVGEP08), or 0.10 ppm (AVGEP10)
Multicomponent	Indices that incorporate several characteristics of exposure, including the phenologically weighted cumulative impact indices (PWCI) (Lee et al., 1987)

It is important to note that, in general, the relative performance of a given index/indices depends on the crop species, the experimental approach and data sets used. Lee et al. (1988), Lefohn et al. (1988), and Musselman et al. (1988) concluded that no single ozone exposure index performed equally well every time. Nevertheless, based on the relative performances of various indices, Lefohn et al. (1988, 1989) concluded that cumulative exposure indices could be used to describe ozone exposures for predicting agricultural crop effects. The findings by Lee et al. (1988) and Lefohn et al. (1989) stressed the importance of using cumulative indices instead of seasonal mean indices. In this regard, Larsen and Heck (1984) and, later, Hogsett et al. (1985b) demonstrated that it was possible for two sites with similar seasonal mean values to have different estimated crop impacts. In the latter study, greater impacts were demonstrated at a site with a lower seasonal mean using fluctuating episodic exposures compared with growth reductions at a similar site with a higher seasonal mean generated via lower, more repetitive daily exposures. Because some of the earlier NCLAN study results were published using the seasonal mean index, an exposure index that does not weight the higher hourly average concentrations, it has been difficult to use some of the results previously published. However, re-analysis of the NCLAN data, using alternative cumulative exposure indices, has allowed investigators to evaluate exposure-response relationships.

Additional insight concerning the possible problems associated with using a seasonal mean can be found in works published by Manning and Krupa (1992) and Legge and Krupa (1990). In general, the frequency distributions of hourly average concentrations (all 24 hours included) of ambient ozone exposure profiles do not exhibit a normal distribution. Rather, the frequency distribution of hourly ambient ozone concentrations is best described by the numerical functions of the Weibull family (Lefohn & Benedict, 1982; Legge & Krupa, 1990). In these distributions, there is a frequency peak to the left at low ozone concentrations, with a tail to the right towards high concentrations. The computation of arithmetic means with such non-normally distributed data is statistically inappropriate and can lead to artifacts in modelling ozone exposure- and crop-response relationships (Krupa & Kickert, 1987b). To the contrary, use of the geometric mean or the median value is free of the influence of this non-normal type of frequency distribution of the data. This approach, however, has not gained widespread acceptance and has been only occasionally referenced as a potential modelling approach for ozone exposure- and crop-response (Larsen & Heck, 1976). In spite of its suitability to non-normally distributed data, it too suffers from the drawback that it condenses the exposure variability in a single value.

With the trend towards a cumulative type expression of ozone exposure as a more biologically relevant methodology, several studies (Lefohn & Benkovitz, 1990; Pedersen & Lefohn, 1994; Lefohn & Foley, 1992) have attempted ‘real world’ application of these experimentally derived exposure indices to determine if they adequately capture the important features of ambient ozone exposure and vegetation impact. These studies have demonstrated the weaknesses of an averaging approach to exposure and have also pointed out limitations in a cumulative index approach, in that this method may require additional consideration of the frequency of high concentrations (Lefohn et al., 1992). For example, over a 100-day growing season, it is possible for two sites to end up with the same SUM60 value but have quite different frequency and intensity profiles of hourly ozone levels. One site could have a few episodic conditions resulting in very high levels over short periods of time and levels below 60 ppb for the remainder of the season. The other could have a larger number of days when ozone levels only marginally exceeded 60 ppb and few or no days when the hourly levels were high. The mathematics of the SUM60 for these two sites could yield a similar SUM60 value but, obviously, the frequency and intensity of the ozone profile could be dramatically different, resulting in a different biological impact.

Contrary to the previous conclusions that the higher hourly average concentrations should be provided greater weight than the mid- and low-level values, several papers have appeared recently in the literature that concluded that the mid-level ozone concentrations contribute more to vegetation effects than the higher values. Krupa et al. (1994) concluded that:

- hourly average ozone concentrations between 0.05 and 0.087 ppm (i.e., mid-range concentrations) may be the most important contributors to crop losses; and
- hourly average concentrations above 0.087 ppm may not be as important in predicting yield loss.

To arrive at these conclusions, the authors selected several data sets from the NCLAN sites at which: yield for plants in non-filtered chambers was the same as yield in ambient air plots; and plant yield in non-filtered chambers was less than plant yield in carbon filtered chambers. An approach was used whereby the cumulative frequency distribution (CFD) of cases with statistically significant negative yield effects (CF>NF) were combined and compared with selected no yield effect studies (CF=NF). The CFD is defined as follows:

CFD50–87 = Total # Hours of Ozone $\geq$ 50 and $\leq$ 87 ppb÷ (Total # of Hours of Ozone $\geq$ 50 ppb)

The CFD approach utilized ozone data for a 24-hour period over the days of the growing season in which the individual NCLAN experiments were operational.

In a study in Germany, Grünhage et al. (1993) and Grünhage and Jäger (1994) reported that mid-range levels of ozone might be more important than high levels in response of plants to ozone exposure. In the 1993 study, Bel-W3 tobacco was used to examine the relationship between ozone flux and plant injury. The results from this study, which pointed to the importance of mid-range levels of ozone in the development of ozone injury, using this highly sensitive ozone-indicator plant, were similar to the earlier findings of Tonneijck and Bugter (1991). In the Grünhage and Jäger study, it was concluded that the conductivity of ozone into plants was normally low during the times of the day when ozone levels were high.

Legge et al. (1995) report that their results using both NCLAN and the European Open-Top Chamber Programme (EOTCP) data show that the cumulative frequency of occurrence of intermediate or moderate hourly ozone concentrations is important in crop yield-loss response. However, unlike their NCLAN findings, which showed that the cumulative frequency distribution (CFD) of hourly ozone concentrations between 0.050 and 0.087 ppm was the best predictor of crop response in the U.S., the corresponding results (using a modified statistical format due to EOTCP design differences) from the EOTCP showed a range of 0.035-0.060 ppm as being important in Europe. While it is concluded that these results demonstrate the importance of moderate hourly concentrations in inducing adverse crop-yield response, the authors underscore the fact that these conclusions do not negate the importance of peak hourly ozone concentrations, if such levels occur during periods when both optimal atmospheric and plant conductivities coincide.

As result of the papers published positing that mid-range concentrations are of greater importance than high values, a debate in the scientific community has arisen. In summary, the underlying reasons for the debate appear to stem from the use of atmospheric ozone concentrations as a surrogate for plant ozone dose. The findings from these studies have been subject to critical review by scientists who feel that the mid-range argument does not adequately describe plant response to season-long ozone exposure. Musselman et al. (1994) conclude that although these studies "all show a response of ozone sensitive plants to moderate concentrations of ozone, they do not provide conclusive data that sensitive plants are not responsive to higher ozone concentrations. Nor do they provide data that other less-sensitive plant species are more responsive to moderate concentrations than to high concentrations of ozone."

Legge et al. (1995) state that they have not concluded that high concentrations are less phytotoxic than mid-range concentrations; rather, they reason that because high concentrations tend to occur at times when ozone uptake by plants is lower, the actual dose absorbed by vegetation during periods of high ozone concentrations tends to be lower than the dose absorbed during periods of the day when plants experience mid-range concentrations. A summary of the response by Legge et al. (1995) is presented in Table 8.7.

In view of the debate that had emerged in the scientific literature and at conferences and meetings regarding the role of mid-range concentrations in ozone exposure–plant response relationships, (Krupa et al., 1994) and in consideration of scientific concerns raised regarding some of the statistical techniques that had been used in the NCLAN and EOTCP reanalysis (Krupa et al., 1994: Legge et al, 1995), the Vegetation Objective Working Group (VOWG) of the NO_x/VOC Science Program decided to more thoroughly evaluate the CFD exposure–response assessments that had been undertaken and described by Krupa et al. (1994) and Legge et al. (1995). The VOWG's re-analysis was conducted by utilizing all the NCLAN data (negative, positive and no-effect cases) identified by Krupa et al. (1994) and Legge et al. (1995). The analysis of this work was also undertaken to compare the effectiveness of the cumulative frequency based index used by Krupa et al. (1994) (CFD50–87), which focused only on the hourly average concentrations between 50 and 87 ppb, versus concentration-weighted cumulative exposure indices, which utilize a threshold value and place greater emphasis on higher ozone concentrations (i.e. SUM60 and AOT40).

Table 8.7 Summary of main arguments from Legge et al. (1995)

Argument	Supporting studies cited
Ozone exposure conditions in open-top chambers do not reflect ambient exposure	Tonneijck and Bugter (1991) found a tendency for a reduced sensitivity of tobacco (Bel-W3) plants to relatively high ozone concentrations in the Netherlands Krupa et al. (1993) found that sums of all hourly concentrations > 0.040 ppm (SUM04) and > 0.06 ppm (SUM06) jointly proved to be the best predictors of median value of foliar injury on tobacco (Bel-W3) at two geographic locations in NE USA. Sum of all hourly concentrations > 0.07 or 0.08 ppm were not as important in explaining the cause-effect relationship. Grünhage and Jäger (1994) demonstrated that a combination of measured and modelled frequency distributions of differing percentages of leaf area injured on tobacco (Bel-W3) at various ambient concentrations of ozone, converted to their corresponding flux densities, showed that concentrations between 0.05 and 0.09 ppm are likely to have the most effect and may be more important than those > 0.09 ppm.
Ozone uptake and/or foliar injury or yield reduction due to ozone are highest at times when or where the ambient ozone concentrations are moderate	Grünhage et al. (1994) and Schmitt et al. (1995) reported that above two grassland ecosystems, the diurnal pattern of ozone deposition velocities reached peak values before noon, whereas the diurnal pattern of ozone concentrations attained peak values during the afternoon. Grulke (cited by Skelly, 1995) showed that trees of giant sequoia responded to low (ambient) values of ozone, not just high values. Showman (1991) reported that ozone injury to sensitive species was widespread in a moist year with low ozone levels, whereas injury in a dry year with high ozone concentrations was rare. Wieser and Havranek (1993) indicated that the diurnal pattern of ozone flux densities from the air to the needles of Norway spruce peak in the late morning, whereas the diurnal pattern of ozone concentrations peak in the afternoon. Wieser and Havranek (1995) reported that when ambient ozone concentrations were highest, ozone flux to the needles of European larch tended to be restricted by narrowing of the stomatal opening. Ojanperä et al. (1994) observed in OTC experiments that a 40-ppb threshold did not provide a significant correlation with changes in the grain yield of spring wheat, while the inclusion of all ozone concs. below 40 ppb provided an R^2 of 0.93.

Upon reviewing the methodology utilized in the Krupa et al. (1994) and Legge et al. (1995) studies, VOWG members questioned the conclusions that were drawn by the investigators. Concerns were associated with the use of the NCLAN data, the statistical approaches used in the analyses, and the accuracy of the regression analyses.

For its review, the VOWG used two approaches. The first was to focus on the use of the NCLAN data. When all the NCLAN data sets identified for the analysis (i.e., all cases of increased, decreased and no-yield effect between the carbon-filtered and unfiltered treatments where yield in unfiltered chambers was not statistically different than yield in ambient air plots) were pooled, cumulative indices (i.e., SUM06 and AOT40) were more closely correlated with plant responses to ozone than the truncated CFD50-87 index, which focused on the mid-range concentrations. In addition, the VOWG concluded that the inaccurate use of some of the NCLAN data identified cast uncertainty on the strength of the frequency-based CFD of mid-range concentrations as an air quality indicator of long-term (seasonal) adverse effects of ozone on crop yield.

The second approach utilized actual ozone hourly values from Canadian monitoring sites. The truncated CFD50–87 values (mean, maximum and minimum) for the 32 sites in Canada that can be classified as being representative of rural or forested areas were calculated. The truncated CFD50–87 technique provided a poor fit with areas of Canada with documented ozone effects on vegetation. In high ozone impact areas of southwestern Ontario like Simcoe, Long Point, Parkhill, Merlin, Tiverton and Huron Park, where foliar injuries and crop loss effects are well documented, the lowest CFD50–87 values were recorded (range of 0.8805–0.9446). In contrast, the highest possible CFD50–87 values (1.0) were recorded in remote northern areas of Ontario (Experimental Lakes Area), where crop effects have not been documented. This was also the case in areas like Cormack, Newfoundland, and Vegreville, Alberta. In other words, as the CFD50-87 increased, fewer exceedances of 82 ppb were recorded (r = -0.92).

As indicated previously, Legge et al. (1995) emphasized that their work pointed to the importance of mid-range concentrations, but acknowledged that if high concentrations occurred during the times of the day when plants are most sensitive, then they too would be considered important. However, given the manner in which the truncated CFD50–87 is calculated as proposed by Krupa et al. (1994), the VOWG concluded that, under ambient air quality conditions, this type of statement was difficult to rationalize. The occurrence of peak concentrations (values in excess of 87 ppb), defacto reduces the magnitude of the CFD50-87 index proposed by Krupa et al. (1994). The VOWG concluded that, based on the truncated CFD calculation methods, it is difficult to assert the importance of mid-range ozone concentrations of 50–87 ppb, while at the same time acknowledging that peak concentrations may also be important.

Although the scientific debate continues concerning the importance of mid-range versus high concentrations, the VOWG concluded that at present there was little support for the truncated CFD approach. This conclusion was based on the following:

- When all the NCLAN data sets identified for the analysis (i.e., all cases of increased, decreased and no-yield effect between the carbon-filtered and unfiltered treatments where yield in unfiltered chambers was not statistically different than yield in ambient air plots) were pooled, the two, cumulative indices (SUM06 and AOT40) were more closely correlated with plant responses to ozone than the CFD of the mid-range concentrations (CFD50-87).
- Inaccurate use of some of the NCLAN data was identified; in addition to the foregoing comparative analysis, this cast uncertainty on the strength of the frequency-based CFD of mid-range concentrations as an air quality indicator of long-term (seasonal) adverse effects of ozone on crop yield.
- The truncated CFD50–87 technique provided a poor fit with areas of Canada with documented ozone effects on vegetation.

Based on the above reasons, the VOWG made the decision to focus on cumulative exposure indices.

Alternative cumulative exposure indices

The discussion that follows is a summary of the analysis undertaken by the Vegetation Objective Working Group of alternative forms of cumulative exposure indices. For the purposes of this discussion, the U.S. approaches are cited in their native form, i.e., in units of ppm; whereas the Canadian equivalents are cited in units of ppb. Crop yield response to ozone is inferred from a large collection of studies; in order for the results of different studies to be pooled together, the ozone exposures received by the plants must be normalized into a common expression that is a substitute for “dose”. The NCLAN data for crop loss have used SUM06 (SUM60) to describe the exposure; many studies since that time have also described exposures in terms of SUM60. Much of the European work has used AOT40 to describe experimental exposures of ozone to plants. Other than these two data bases, there is a vast array of studies, both of acute and chronic exposures, for which neither AOT40 nor SUM60 were or can be calculated. This is because the air quality throughout the study was not monitored in a manner consistent with the calculation of these indices, and the studies are extremely difficult to harmonize with each other, and with the NCLAN data set. So, the choice of SUM60 as a candidate exposure index for evaluating plant response to ozone is supportable from the perspective of being able to evaluate the largest, normalized data base available.

However, because the hourly ozone data for the NCLAN studies were available, it was possible to test other indices of ozone exposure for description of the NCLAN crop yield data. For reasons described in the previous section, the truncated CFD approach was ruled out as a viable option. On the basis of published scientific studies and discussions within the U.S. on the need for an ecologically based secondary ozone standard, it was concluded that the most appropriate form of a vegetation-based air quality index was one that was cumulative in nature, with greater emphasis on peak versus mid-range concentrations and some type of phenological weighting. However, given the lack of phenologically linked dose response information required to develop a phenologically weighted index (this would necessitate a crop-by-crop, tree-by-tree and region-by-region approach), the decision was then focused on threshold-based cumulative indices. The weighting of an index based on sigmoidal curves reflective of potential flux factors (e.g., the W126 index) was also explored briefly, but was ruled out primarily for the reason that it was believed that from a regulatory aspect, this type of index would be complex and difficult to administer.

Consequently, the options for form of an ozone exposure index were reduced to SUM60 and AOT40 forms, both of which express ozone levels as ppb-h. The sections that follow describe how the final decision to adopt a SUM60 index was reached. Although both AOT40 and SUM60 are cumulative in the manner in which they sum ozone exposure values, there are three key differences:

1. The AOT40, by definition, takes ozone levels above 40 ppb into consideration, whereas the SUM60 does not start accumulating the hourly exposure to ozone until the concentrations reach 60 ppb (0.06 ppm).
2. The AOT values are censored by subtracting 40 from all hourly values > 40 ppb (i.e., a reading of 65 contributes 25 to summation process), whereas in the case of the SUM60 the entire value is used in the summation process for concentrations ≥ 60 ppb.
3. The AOT40 and SUM60 indices utilize hourly ozone values from different periods of the day; the AOT40 captures all ozone concentrations during the time of the day when global clear-sky radiation is above 50 W/m^2 during three months (normally May-July). If solar radiation information is not available, the hours from 07:00-21:00 are reported as defaults. In the case of the SUM60, the hourly ‘window’ is a 12-h period (08:00-19:59) using a running, three-month calculation process (for a seasonal SUM60 that is).

The AOT40 and SUM60 indices were evaluated by looking in more detail at a subset of the NCLAN data for which signficant chamber effects could be ruled out (i.e.: for NF = AA as presented in Table 8.8 (only SUM60 results shown). In this subset, exposure / plant response information is limited to a comparison of the charcoal filtered chambers (CF) and the ambient air plots (AA).

From the analysis of this subset (n=22) it was determined that:

1. The best performing indices were the SUM60 (12-h) and the AOT40 (12- and 15-h).
2. Modifying the AOT40 index to censor the data from 60 ppb instead of 40 ppb (effectively making it AOT60) and shortening the daylight period to 08:00 to 19:59 to match the SUM60 format, failed to improve the predictive capability of the AOT index.
3. The cumulative expressions of ozone exposure performed considerably better than the frequency of exceedance of the existing Canadian air quality objective of 82 ppb in predicting yield reductions.

Table 8.8: SUM60 values and Crop yield in a subset of NCLAN data where NF = AA*

Location	Year	Crop	SUM60 Adj.3 Mo. (08:00-19:59)	AA Yield	NF Yield	CF Yield	Yield Ratio NF/CF	Yield Ratio AA/CF
ARGONNE	1981	Maize	14,117	24.2	25.5	25.8	0.990	0.940
	1985	Soybean	18,337	14.9	14.4	14.9	0.966	0.999
	1983	Wheat	17,949	462.0	450.9	412.9	1.092	1.119
	1993	Soybean	23,736	15.4	16.1	17.1	0.940	0.899
Ithaca, N.Y.	1983	Wheat	29,011	33.8	34.4	44.6	0.770	0.757
	1982	Wheat	9,513	70.8	62.1	98.9	0.628	0.716
	1982	Kidney Bean	6,842	1,187.3	1,213.3	987.2	1.229	1.203
	1981	Soybean	990	16.2	15.6	16.3	0.957	0.994
	1980	Kidney Bean	5,073	1,349.4	1,374.9	1,660.2	0.828	0.813
	1984	Clover -Harv.1	12,562	132.3	98.8	52.6	1.876	2.515
	1984	Clover -Harv.2	5,628	39.5	48.4	37.1	1.305	1.066
	1985	Clover -Harv.1	10,279	68.5	23.2	55.5	0.419	1.236
	1985	Clover -Harv.2	7,634	11.0	6.9	13.6	0.507	0.813
Beltsville	1983	Soybean	39,212	17.7	18.2	19.5	0.933	0.908
Raleigh	1984	Clover -Harv.1	19,058	31.6	30.6	36.8	0.831	0.858
	1984	Clover -Harv.2	42,512	32.3	32.1	35.0	0.916	0.924
	1984	Clover -Harv.3	46,165	26.7	30.2	33.9	0.888	0.787
	1984	Clover -Harv.4	16,588	21.9	20.0	20.8	0.958	1.050
	1985	Clover -Harv.1	40,851	14.3	14.1	24.1	0.584	0.592
	1985	Clover -Harv.5	22,917	3.5	0.8	8.2	0.100	0.431
	1984	Soybean	19,422	16.7	16.5	17.7	0.930	0.939
	1983	Soybean	40,754	15.7	16.1	17.3	0.929	0.909

* Adapted from Table 6.3.1 in Report of the Vegetation Working Group (Multistakeholder NO$_x$/VOC Science Program, 1997)

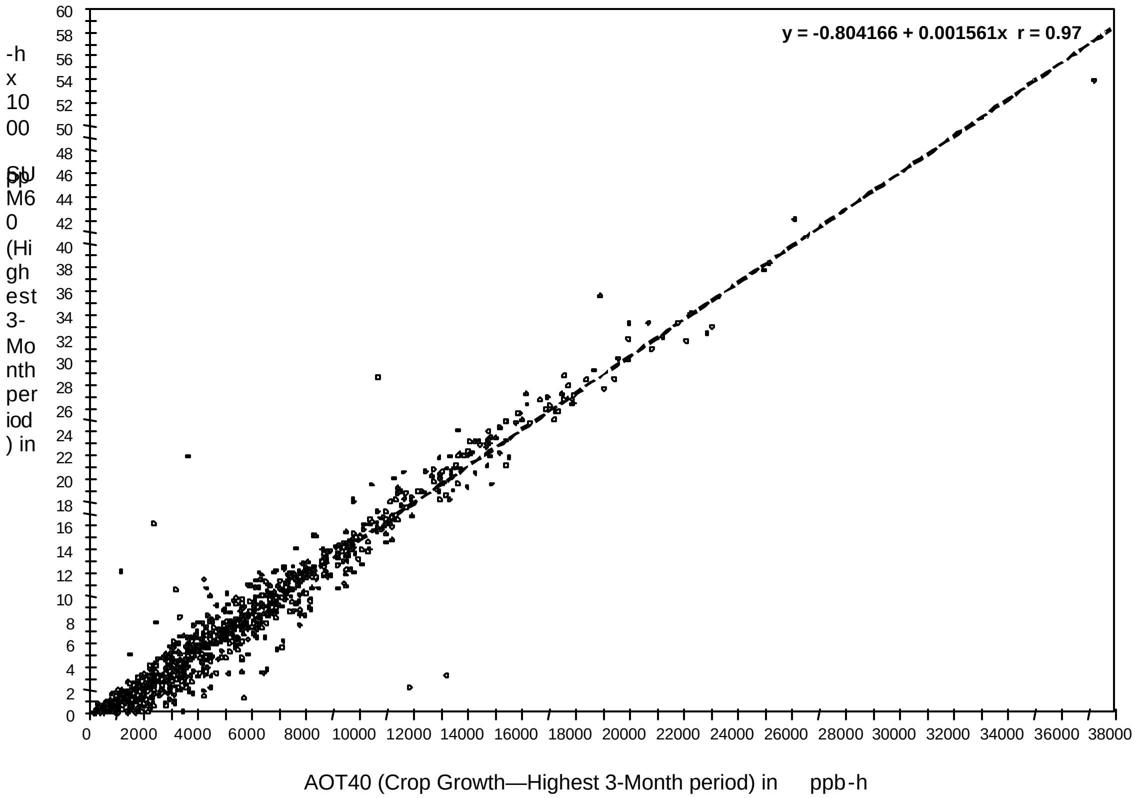
As a final step in the decision to recommend the SUM60 in preference to the AOT40 index, the Canadian air quality data for the period 1980-93 were assessed to explore the relationship between these two possible forms. A regression of these two indices is shown in Figure 8.2, and confirms a high degree of similarity ($r^2 = 0.97$). Therefore, it is concluded that, from an air quality management perspective, the decision to adopt a SUM60 index as opposed to an AOT40 makes little practical difference in terms of assessing the areas of ozone impact on Canadian vegetation.

Given the agreement of the two indices in predicting crop yield response and the high correlation between the two forms when looking at the ambient data, there appears to be no compelling scientific reason to select one over the other. Therefore, other factors were considered, including:

- support for the AOT40 resides primarily in Europe, where experimental studies via the EOTCP have concentrated mainly on three crops (spring wheat, green bean and pasture); although additional crops and trees are now being evaluated, the AOT40 Critical Levels for crops are still restricted to one agricultural species (wheat);
- support for the SUM60 resides primarily in the U.S., where the NCLAN program has provided exposure/response data for 15 crop species (corn, soybean, wheat, alfalfa, clover, fescue, tobacco, sorghum, cotton, barley, peanut, potato, lettuce, turnip and dry bean);
- although there may be greater similarity in climate between the major ozone impacted regions of Canada and some of those in Europe, where the EOTCP studies were conducted, than would be the case for some of the U.S. NCLAN sites, there was consensus that other factors (levels of other atmospheric contaminants, differences in the genetic composition of plants under study) in the European setting may be important and would favour the selection of the SUM60 over the AOT40; and
- given the geographical location of Canada relative to the U.S., and the importance of a coordinated approach to the resolution of air quality issues of such regional and transboundary nature, it was concluded that the harmonization of an air quality index to protect vegetation in both countries could lead to improved efforts in emission reduction strategies.

Based on the factors described above, a decision was reached by the VOWG to recommend the use of SUM60 as an index for describing ozone exposure-vegetation response relationships. This decision is supported by the Working Group on Air Quality Objectives and Guideines. However, it is noted that although the SUM60 clearly encapsulates some aspects of plant exposure that are important in the response (i.e. cumulative exposure over a time period and the relative importance of peak concentrations), there are other factors influencing the exposure-response relationship that are not accounted for in the SUM60 index (e.g. phenology, time of day). In the future, it may be possible to develop a more biologically relevant index.

Figure 8.2: Relationship Between SUM60 and AOT40—All Canadian Monitoring Sites (1980–1993)



8.2.3 Exposure-Response Relationships for Chronic Effects

Growth Reduction to Agricultural Crops

One of the most critical decisions that must be made in any assessment of season-long yield reduction is to establish the limits of experimental certainty with respect to final yield or biomass loss. Based on recent analyses undertaken in Europe (Fuhrer, 1994) and the U.S. as part of their Critical Level and Secondary Standard development processes, respectively, the lowest possible precision from experimental, season-long ozone exposures involving crops has been estimated at from 5-10% (i.e., loss estimates below 5-10% would be within the range of experimental error). Given the additional variability and uncertainty regarding the application of the experimental findings from open-top chambers to real-world field conditions, a yield loss minimum value of 10% is utilized in this assessment. It is recognized that a 10% yield-level decision could, under many agricultural situations, represent virtually all of the economic profit margin for a typical crop producer. However, given the uncertainty that currently exists in the available experimental findings it has been concluded that this is the best that can be achieved at this time.

Another factor that must be considered in the process of trying to define an ambient ozone level above which effects on Canadian vegetation occur, is that the research cannot possibly cover all crops/cultivars, trees or species of native vegetation growing in a country the size of Canada. The recommendation of an ‘effects-level‘ will arise from a data base which contains information on perhaps half of the ‘important’ agricultural and woody tree species, and virtually no native herbaceous species.

The NCLAN experimental protocol was designed to produce crop exposure-response data (See Box 1). In the U.S. EPA review of the NCLAN data to support discussion on the form and level of a secondary standard for ozone, a subset of the NCLAN data was identified as being most appropriate for this type of evaluation (U.S. EPA, 1996). In order to use these data to develop LOAELs in a Canadian context, a further subset was created by removing those crops not grown in Canada as well as those evaluated under Californian growing conditions. This set of crops, with 3 month, 12-h SUM60 values corresponding to 10% yield loss levels are shown in Table 8.9 (n = 42). The 10% yield loss levels were calculated from individual regression analyses of yield data from all NCLAN studies on a particlar crop (U.S. EPA, 1996). There is insufficient information in this subset to identify NOAELs.

Box 1: NCLAN Protocol[1]

The U.S. National Crop Loss Assessment Network (NCLAN) Program was set up in 1980 to provide the data needed to assess the economic consequences of air pollution on major agricultural crops. This called for experiments to be conducted to better the relationships between crop yield and different doses of O_3, SO_2 and NO_2, individually and in combination. Initially, the focus of NCLAN was on O_3 because this information was required as part of the review in the U.S. of the secondary National Ambient Air Quality Standard (NAAQS) for ozone.

Six field sites in the NE, SE (2), Central, SW and NW of the United States were established to study ozone exposure - crop yield relationships for a number of important crops. The experimental protocol was designed explicitly to minimize differences in growing conditions, to use realistic pollutant concentrations and to allow analysis of the data by both ANOVA and regression techniques. OTCs (3 m diameter) and standardized ozone dispensing and monitoring systems were utilized. Each experiment consisted of a series of 4-6 ozone treatments replicated 4 times in a randomized block design for a total of 24 plots per site per crop cultivar.

The standard treatments were as follows:

AA	Ambient air plot, no chamber.
CF	OTC plot, charcoal filtered air. Control plot, where ozone concentration was approximately 25 ppb, intended to represent natural background ozone.
NF1	OTC plot, non-filtered air. Ozone concentration approx. equal to ambient air.
NF2	NF1 plus an additional 30 ppb ozone.
NF3	NF1 plus an additional 60 ppb ozone.
NF4	NF1 plus an additional 90 ppb ozone.

For NF treatments, ozone was added for 7 hours per day between the hours of 0900 and 1600 (Standard Time). Ozone concentrations within the plots were monitored at canopy height, for 2-3 minutes about 2-3 times per hour. The NCLAN adopted a seasonal 7 hr/day mean O_3 concentration as its index of plant exposure. The 0900 - 1600 time period was selected to include the hours of the day when plants are most active and when ozone concentrations are generally highest. The “season”, as defined by the NCLAN protocol, covered only the period of time during which O_3 treatments were administered, and therefore varied with each crop.

Plants were harvested from all plots when CF plants reached maturity. Based on the protocol, comparisons of NF1 plot yields with AA plot yields were used to test for chamber effects. Plot yields were reported as both absolute yields and as a percentage of predicted yield at the control concentration (CF plot, O_3 concentration approx. 25 ppb). Dose-response relationships were first developed for individual crop cultivars. Then, where possible (i.e. where homogeneity across the individual responses existed), combined dose-response functions were calculated as the simple average of individual loss functions. A number of linear and non-linear dose-response functions have been developed and evaluated using the NCLAN data.

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[1] The information in this Box was compiled from the following sources: Heck et al., 1982; Heck et al., 1983; Heck et al., 1984). The original papers should be referred to for further detail on methodological aspects of the NCLAN Program, particularly regarding the objective of developing better physiological models of plant response to air pollution, a subject not covered in this Box.

Table 8.9 Summary of NCLAN SUM60 index values resulting in a 10% yield loss in NCLAN studies.

Crop Evaluated[1]	Cultivar	Moisture Status	12-hour SUM60 (ppb-h)
Corn (L)[2]	PIO		41,600
	PAG		55,800
Kidney Bean	CAL LT RED		15,200
Kidney Bean (L)	CAL LT RED		17,200
Peanut (L)	NC-6		36,200
Potato	NORCHIP		9,900
	NORCHIP		20,300
Sorghum	DELALB		67,600
Soybean	CORSOY		15,300
	CORSOY		42,200
	AMSOY		32,800
	PELLA		18,200
	WILLIAMS		15,500
	CORSOY	Dry	71,200
	CORSOY	Wet	70,000
	CORSOY	Dry	89,100
	CORSOY	Wet	62,200
	CORSOY	Dry	10,200
	CORSOY	Wet	11,800
	WILLIANS	Dry	21,100
	WILLIAMS	Wet	14,800
	HODGSON		8,400
	DAVIS		13,800
	DAVIS		23,400
	DAVIS	Dry	57,100
	DAVIS	Wet	35,200
	DAVIS	Dry	45,900
	DAVIS	Wet	24,100
	YOUNG	Dry	38,800
	YOUNG	Wet	25,000
Tobacco (L)	MCNAIR		24,400
			cont.

Table 8.9 Summary of NCLAN SUM60 index values resulting in a 10% yield loss in NCLAN studies.

Crop Evaluated[1]	Cultivar	Moisture Status	12-hour SUM60 (ppb-h)
Turnip (T)	JUST RIGHT		7,400
	PURPLE TOP		5,900
	SHOGOIN		6,600
	TOKYO CROSS		9,300
Wheat	ABE		25,100
	ARTHUR		21,300
	ROLAND		7,400
	ABE		34,800
	ARTHUR		27,700
	VONA		2,900
	VONA		7,700

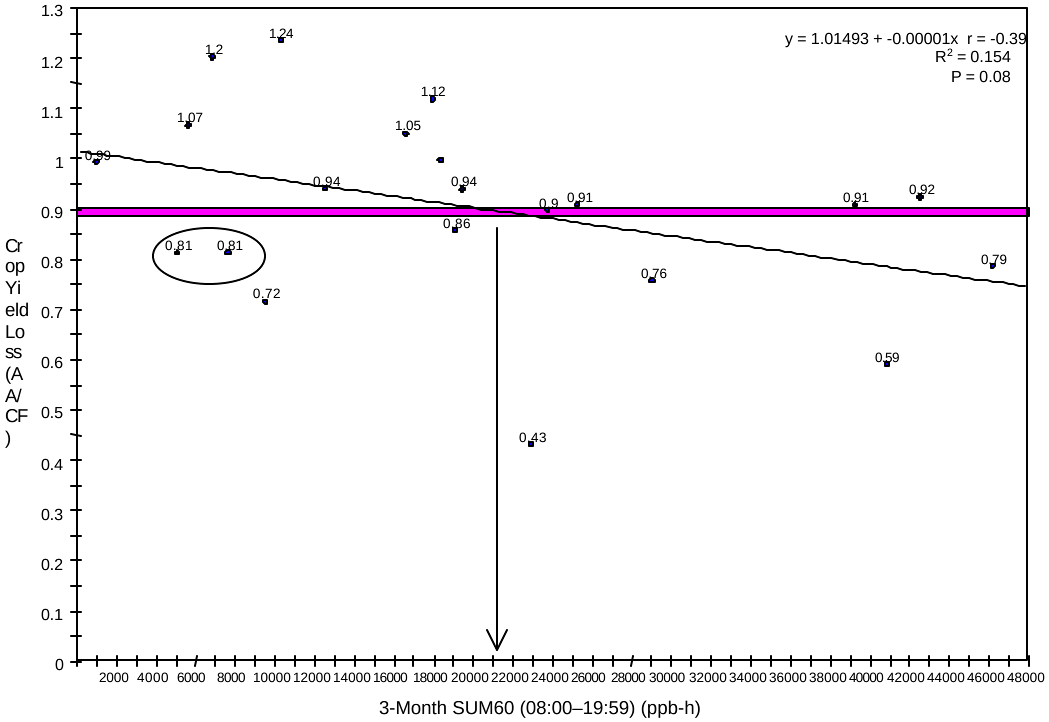
[1] excluding cotton and crops assessed in California.

[2] (L) log transformation used to stabalize the variance (T) yield expressed as g/plant. A weibull model was fit to all other studies, and all other yields are expressed in kg/Ha.

The lowest SUM60 value at the 10% yield loss level is 2,900 ppb-h for wheat cultivar VONA. The next most sensitive species were turnips and other wheat cultivars spanning the range 5,900 to 7,400 ppb-h. The SUM60 level corresponding to the median crop biomass loss at the 10% yield loss level is 38,000 ppb-h (U.S. EPA, 1996, Figure 5-23). At an expert workshop convened in January 1996 on the ozone secondary standard, there was consensus that a more conservative approach should be taken, namely that the ppb-h when 25 and 35% of the crops had 10% or more yield loss should be considered (Heck and Cowling, 1997). This corresponds to 15,000 and 20,000 ppb-h respectively.

To further the identification of a LOAEL, the data for which chamber effects were considered negligible (Table 8.8) were reviewed again (Legge et al. 1993). Figure 8.3 presents the regression analysis of these data (i.e. between crop yield loss and the 3-month SUM60). From the regression curve of Figure 8.3, the level at which 10% yield loss is predicted is about 21,000 ppb-h. The LOAELs observed from this analysis were 5,000 to 7,700 ppb-h, as indicated by the circled data points in Figure 8.3. At these SUM60 levels, the two crops in question experienced a 20% yield loss (approximately). Although the LOAELs from the two data sets (Table 8.9 and Figure 8.3) are for slightly different endpoints (10% vs. 20% yield loss), the similarity in the range of LOAELs lends some confidence to these levels. Similarly, the average 10% yield loss levels from the two data sets are also reasonably close (38,000 vs. 21,000 ppb-h).

Figure 8.3 Relationship between SUM60 and crop yield loss (AA/CF) for NCLAN data subset where NF=AA.



Note: SUM60 values for two crops (Argonne-1981-Maize and Raleigh-1983-Soybean) were selected from the 3-month period corresponding with reproductive growth. Ithaca 1984 clover Harvest 1 excluded as an outlier.

In terms of estimating plant response under conditions of enhanced ozone exposure it was reasoned that if the plant response to ozone was enhanced as a result of the use of experimentally elevated ozone treatments in the NCLAN studies, then the SUM60 values for 10% yield loss derived from the full treatment regression approach (listed in Table 8.10 which includes only crops from Table 8.9 that match those in Table 8.8) using all experimental additions of ozone should be out of line with the analysis of the NCLAN subset where NF = AA (Table 8.8). The average SUM60 value corresponding to a 10% yield loss level for the three crops in common (kidney bean, soybean and wheat) from Table 8.10 was 29,200 ppb-h. To compare, the average SUM60 value corresponding to a 10% yield loss level when no ozone was added to the chambers (Figure 8.3 and Table 8.8) was ~21,000 ppb-h These two estimates are quite close considering the uncertainties associated with using the NCLAN data for this type of analysis. If anything, it appears as if plant response under experimentally elevated ozone concentrations is less than under the ambient exposure conditions.

Table 8.10: Crop yield loss selected for comparison with ambient air exposure treatments from the Legge et al. NCLAN re-analysis.

Crop Evaluated	Cultivar	Moisture Status	12-hour SUM60 (ppb-h)
Kidney Bean	CAL LT RED		15,200
Kidney Bean (L)	CAL LT RED		17,200
Soybean	CORSOY		15,300
	CORSOY		42,000
	AMSOY		32,800
	PELLA		18,200
	WILLIAMS		15,500
	CORSOY	Dry	71,200
	CORSOY	Wet	70,000
	CORSOY	Dry	89,100
	CORSOY	Wet	62,200
	CORSOY	Dry	10,200
	CORSOY	Wet	11,800
	WILLIANS	Dry	21,100
	WILLIAMS	Wet	14,800
	HODGSON		8,400
	DAVIS		13,800
	DAVIS		23,400
	DAVIS	Dry	57,100
	DAVIS	Wet	35,200
	DAVIS	Dry	45,900
	DAVIS	Wet	24,100
	YOUNG	Dry	38,800
	YOUNG	Wet	25,000
Wheat	ABE		25,100
	ARTHUR		21,300
	ROLAND		7,400
	ABE		34,800
	ARTHUR		27,700
	VONA		2,900
	VONA		7,700
		Average	29,200

Obviously, this type of assessment is also subject to considerable experimental error (due mainly to the utilization of a small subset of the NCLAN data; however, based on conclusions reached by vegetation experts at the Southern Oxidant Study (SOS) Workshop in Raleigh, NC (Heck & Cowling, 1997) and by others involved in the two major ozone air quality standard development efforts in Europe and the U.S., and subject to all the normal caveats associated with the development of air quality criteria, there appears to be no compelling reason to discard the NCLAN studies based on these concerns. The earlier work in California using air quality gradients (Musselman et al., 1988) as well as the numerous studies documenting vegetation impacts via the use of chemical protectants also provides support for using the NCLAN dataset.

Therefore, the relative yield loss data from the crops which received experimentally elevated ozone concentrations appears equally valid to those for which chamber effects are considered negligible, for estimating LOAELs and average 10% yield loss levels. In fact it is probably better because it spans a broader range of ozone concentrations and includes more crops.

However, considering the limitations of the NCLAN experimental protocol and dataset for purposes of identifying LOAELs (Box 1), it was considered inappropriate to simply select the lowest SUM60 from Table 8.9. Based upon the grouping of wheat and turnip harvest yield reductions in Table 8.9, a more conservative estimate of the LOAEL for reduced yield due to ozone exposure is in the range of 5900 to 7400 ppb-h

Additional Support for SUM60 Form and LOAEL Estimates for Crop Yield Reductions

The selection of the recommended form (SUM60) and LOAEL estimate is further supported by a review of the the chemical protectant studies that had been undertaken in Ontario during the period 1976-81 (most under research contracts between the Ontario Ministry of Environment and Energy (MOEE) and the University of Guelph). This required a reanalysis of all ozone-monitoring data from sites located as close as possible to the research sites. In a few cases, the experimental sites were too far from monitoring sites for these to provide useful ozone exposure information. These sites were therefore discarded. For a discussion of the detailed analysis the reader is referred to the Report of the VOWG (Multistakeholder NO_x/VOC Science Program,1996).

Yield loss data for a total of four crops (white bean, potato, tomato and cucumber) were assessed relative to the SUM60 (June–August) and exceedances of the 82 ppb hourly objective during the same 3-month period. The conclusions drawn from this analysis are summarized below.

- In the case of the all-crop analysis, a marginally significant relationship was found between SUM60 and yield ratios; however, the variability was high and precluded any meaningful predictive analysis.

- In the case of white beans, the relationship was considerably improved. However, in all cases, exposures were at levels in excess of the estimated LOAEL range of 5,00 to 7,400 ppb-h. Thus, a conclusion regarding the effectiveness of a 3-month SUM60 in this range to provide protection to this crop cannot be drawn from these data.

- In all cases except tomato, the SUM60 index of air quality was measurably better than exceedances of an hourly level of 82 ppb in terms of its ability to predict crop yield loss.

Although the analysis of this historical research appears to signal a weak relationship between the SUM60 index and crop response, caution must be exercised in the interpretation of these data for several reasons.

- In almost every report summarizing the findings of this research, it was pointed out that the chemical protectant (EDU) was unable to provide complete foliar injury protection and, accordingly, the EDU treatment may not be an accurate measure of growth/yield potential under ozone-free conditions; similar conclusions regarding the interpretation of chemical protectant studies were reached by Heagle (1989).

- In almost every study, a high degree of cultivar variability was experienced in the response to EDU application; this negated any attempt to elucidate causal relationships; again, Heagle (1989) expressed similar concern regarding the effectiveness of this material as reflected in the wide variability in the reported research findings.

Given these factors, the only conclusion that can be drawn from these studies is that yield losses of greater than 10% were frequently observed at SUM60 values as low as 9,000-10,000 ppb-h. Given the ineffectiveness of the EDU applications in terms of foliar injury response, it is not unreasonable to conclude that yield reductions were probably occurring at levels well below these values.

Growth Reduction to Trees

In the late 1980s, the U.S. EPA developed a program to assess the impact of ozone on forest trees of the U.S. via an OTC exposure protocol similar to that of the NCLAN. The findings of that assessment have been summarized by Hogsett et al. (1995) and also in the most recent EPA Staff Paper (1996). The method used in this study for determining the impact of ozone on forest trees is fully described in Hogsett et al. (1997), although tree response data are not presented and most of the tree response data from which this analysis was derived are cited as personal communication. Because the data are not available for inspection, it is not possible to display the exposure-responses for the various species on one graph as was done for the crop yields. However, the regression relationships between the normalized exposure (SUM06) and relative loss of biomass for all the cultivars and harvests were presented in Hogsett et al. (1997) as a single pooled Weibull relationship connecting the 50th percentiles of the range of relative biomass losses at values of SUM06 ranging from 10 to 60 ppm-h (10,000 to 60,000 ppb-h). Because this calculation collapses all species and cultivars into one exposure-response relationship, the SUM60 value corresponding to a 10% loss of biomass in individual species has been extracted from an earlier presentation (Hogsett et al., 1995) and is presented in Table

8.11. The values range from 4.4 ppm-h (4,400 ppb-h) for black cherry to 250 ppm-h (250,000 ppb-h) for Douglas Fir and Red Alder.

Table 8.11: Exposure-response data for 10% level of biomass loss, for trees exposed in OTCs to ozone .

Tree Species Evaluated	12-hour SUM60 (ppb-h)
Aspen – wild	19,100 15,800 43,700 55,900 55,400 18,700
Aspen 216	14,700
Aspen 253	8,100
Aspen 259	4,700
Aspen 271	13,300
Aspen 216	9,500
Aspen 259	5,200
Aspen 271	29,600
Aspen – Wild	15,000
Douglas Fir	89,300 250,000 90,800 94,400 72,000 70,800 63,000
Ponderosa pine	17,900 26,300 18,500 27,100 11,300 21,600 19,500 14,900 27,900 55,200 cont.

Tree Species Evaluated	12-hour SUM60 (ppb-h)
	43,400.
Red Alder	32,100 17,900 79,000 38,008 250,000 21,800
Black Cherry	6,600 4,400
Red Maple	71,700
Tulip Poplar	23,400 19,900 14,700
Loblolly GADR 15-91	71,000
Loblolly GAKR 15-23	212,100
Sugar Maple	25,300 23,800
E. White Pine	21,600 31,500
Virginia Pine	191,200

Source: Hogsett et al. 1995

The table shows that the SUM60 LOAEL estimates at the 10% biomass loss level, range from 4,400 to 6,600 ppb-h, based upon the response of black cherry and aspen 259 tree species.

8.2.4 Form of an Exposure Index – Acute Effects

Given the importance of protecting plants from both acute and chronic foliar injuries which may negatively impact crop quality and marketability, the development of a short term exposure index was considered. This was underscored in a publication of Lefohn et al. (1992), who suggested that the seasonal, cumulative-index approach to assessing crop response to ozone exposure may require additional consideration of the frequency and episodicity of short-term, high concentrations (since these are not specifically accounted for in the utilization of a seasonally-based cumulative index), if plants are to be protected from short term injury also.

Because there was no systematic attempt within the NCLAN program to draw relationships between ozone exposure and foliar injury, and because the work which forms the basis for the European short-term AOT40s was difficult to translate into protection provided via a SUM60 index under Canadian growing conditions, data from ongoing investigations into foliar injury in

Ontario and from the database of air quality ozone monitoring at rural and forested sites across Canada were utilized.

The following key issues were addressed:

- Is it necessary to implement a short-term index of ozone air quality, or will a 3-month seasonal SUM60 accurately describe the relationship between exposure and acute acute injury as well?
- If necessary, what form of short-term index best describes the relationship between acute exposure and foliar injury development?

These questions were addressed first by examining foliar-injury development on two crops in Ontario where such injury had been documented and could be linked with ozone air quality.

Ontario Case Studies

<u>Case 1: Radish</u>

In 1994, the MOEE investigated a case of extensive damage to a crop of radish in the Hamilton area. The foliar symptoms were characteristic of ozone-induced injury and had affected two harvests. In the first harvest, injury was estimated at 11-35% of the leaf area, while in the second harvest (five days later), injury was less severe, ranging from 2 to 10%. These symptoms had a negative impact on the appearance and, ultimately, the marketability of the crop.

In an attempt to explore the relationship between the severity of the foliar symptoms and several potential short-term indices, and to contrast these indicators of ozone air quality with the three-month SUM60 and exceedances of the existing one-hour ozone objective of 82 ppb (designed to provide protection against foliar symptoms), the air quality data from three of the closest air quality monitoring stations in the vicinity of the farm were analyzed. The results are presented in Table 8.12. Based on this information, the following conclusions were drawn:

- severe foliar injury was documented at a site where the average three-month SUM60 level was under 6,700 ppb-h (within the LOAEL range presented in section 8.2.3);
- a SUM60 calculated from ambient ozone concentrations over a three- or five-day period during the previous 15 days (prior to injury appearance) was unable to differentiate the severity of injury between the two plantings (injury severity levels of 11-35% vs. 2-10%);
- a SUM60, calculated from ambient ozone concentrations over a one-day period, did differentiate between the injury experienced in the two plantings (one-day SUM60 of 918 vs. 750 ppb-h for 11-35% and 2-10%, respectively);

- the frequency of exceedance of the existing hourly ozone objective of 82 ppb during the previous 15 days was also related to the degree of foliar injury (12 vs. 5 hours of 82 ppb for 11-35% and 2-10%, respectively).

Table 8.12 Assessment of foliar injury to radish and ozone levels at monitoring sites near Hamilton, Ontario (1994)

Station No.	3-month basis (April-June)		Previous 15 days (prior to harvest)							
			Harvest #1 (May 17-June 2) 11-35% foliar injury				Harvest #2 (May 24-June 7) 2-10% foliar injury			
	SUM60 (ppb-h)	Total hours 82 ppb	Max. 1-day SUM60 (ppb-h)	Max. 3-day SUM60 (ppb-h)	Max. 5-day SUM60 (ppb-h)	No. hours 82 ppb	Max. 1-day SUM60 (ppb-h)	Max. 3-day SUM60 (ppb-h)	Max. 5-day SUM60 (ppb-h)	No. hours 82 ppb
29,105	5837	16	860	1,374	1,393	11	718	1,374	1,393	5
29,114	8396	21	884	1,675	1,675	13	816	1,675	1,764	6
29,118	5841	11	1,010	1,485	1,374	11	716	1,485	1,485	4
Average	6691	16	918	1,511	1,481	12	750	1,511	1,547	5

Therefore, the two forms that appeared to provide the best fit with the severity of the injury were the number of exceedances of the existing one-hour ozone objective (82 ppb) and a cumulative one-day SUM60.

Case 2: White Bean

In 1995, the MOEE undertook a more detailed evaluation of foliar injury to the white bean crop in southwestern Ontario (Emerson, 1996). Unlike the normal, ongoing assessment that has been undertaken since the late 1970s, the 1995 assessment included an evaluation of foliar injury on about 90 varietal plantings located at nine different sites. The plants were rated on the basis of an injury index (scale of 0-100) by inspection of each variety plot for foliar ozone damage (stippling/bronzing). A numerical injury rating (from 0 to 6) was assigned that represented the average severity of injury to the plot as shown below:

Rating	Criteria
0	No oxidant symptoms observed
1	Scattered stippling on a few of the oldest leaves
2	Scattered stippling over most of the leaves
3	Moderate stippling or bronzing over a few of the leaves
4	Moderate stippling or bronzing over most of the leaves with some coalescence into flecks
5	Severe stippling or bronzing coalescing into necrotic flecks on many of the leaves; some premature leaf senescence and initial defoliation
6	Severe stippling or bronzing and coalescence on almost all leaves; plants prematurely senescent and defoliation occurring

The seven injury rating levels fall into five general injury-severity categories: no injury (0), trace (rating 1), light (ratings 2-3), moderate (rating 4) and severe (ratings 5-6). In order to compare the overall severity of ozone bronzing/stippling on white beans between locations, an injury scoring method was devised such that the injury ratings could be reduced to a single numerical score for each location and year. The injury-index scores were derived by calculating the percentage (%) of observations in each injury category (relative to total number of observations), and then multiplying the percentage (decimal) values by weighting factors as follows:

Trace (x 5)

Light (x 25)

Moderate (x 50)

Severe (x 100)

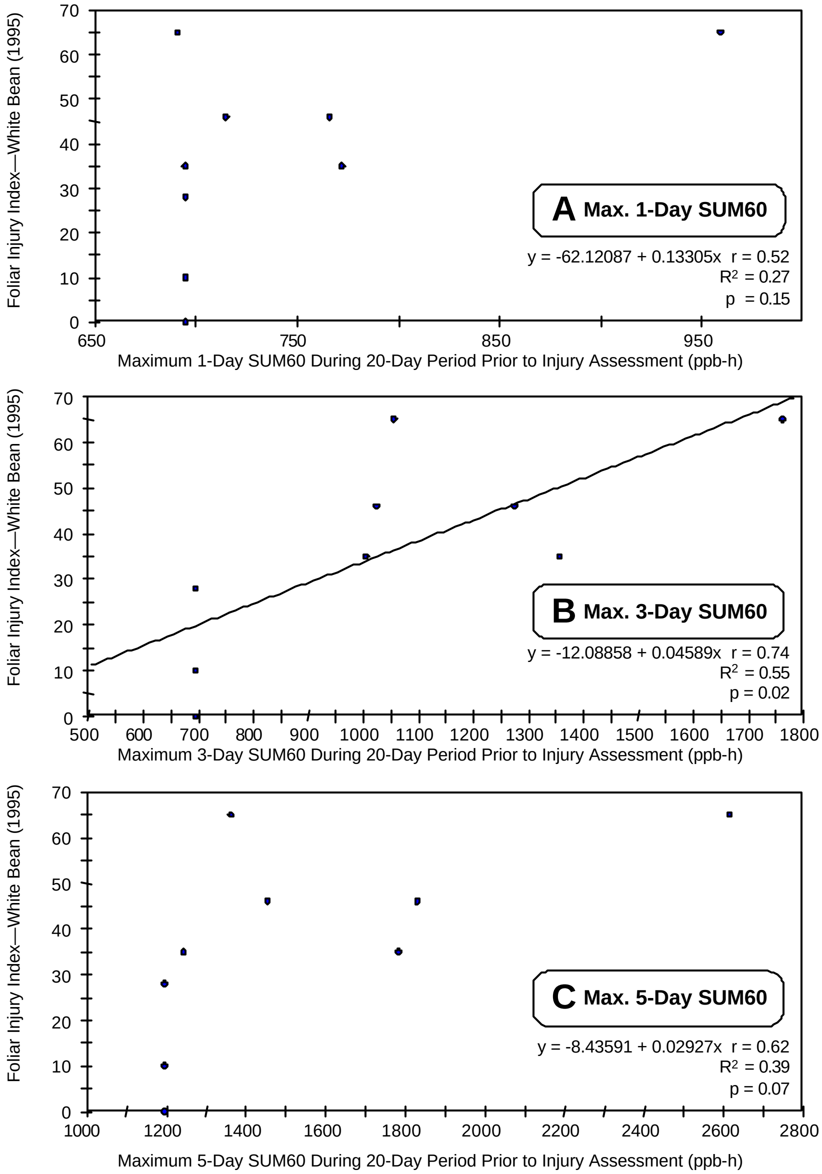
The total injury index score for each location/year was calculated by totaling the weighted scores for all injury categories. For example, if 30% of plots fell in trace category (0.3 x 5 = 1.5), 30% in light (0.3 x 25 = 7.5), 20% in moderate (0.2 x 50 = 10) and 20% in severe (0.2 x 100 = 20), the total injury index score was 1.5 + 7.5 + 10 + 20 = 39, out of a maximum 100. For purposes of interpretation, a score between 1-20 was classed as trace, between 21-35 as light and between 36-50 as moderate. A score of greater than 50 was classed as severe.

As for the radish injury assessment, the ozone air quality at nine sites (extrapolated from the closest rural monitoring stations in 1995) was assessed for a relationship with injury severity on white bean (Table 8.13). Statistical analyses were performed to explore the relationships between three potential short-term cumulative ozone indices (1-day, 3-day and 5-day SUM60), the existing 1-hour ozone objective (82 ppb) and the 3-month SUM60. Plots of the three short-term SUM60 indices and injury index severity are shown in Figure 8.4.

Table 8.13: Assessment of Potential Short Term Indices Based on Foliar Injury to White Bean in Ontario (1985)

Year	Crop Location	Previous 20-Day Period				June–August Period		Foliar
		Max. 1-day SUM60 (ppb-h)	Max. 3-day SUM60 (ppb-h)	Max. 5-day SUM60 (ppb-h)	No. hours = > 82 (ppb)	3–Month SUM60 (ppb-h)	No. hours = > 82 (ppb)	Injury Index (0–100)
1995	Elora	766	1275	1829	3	17911	44	46
1995	Harrow	959	1762	2615	20	28942	87	65
1995	Ridgetown	866	1559	2199	15	24735	72	35
1995	Huron Park	691	1055	1361	3	16630	48	65
1995	Brussels	718	1110	1460	6	16453	47	46
1995	Shetland	721	915	1391	7	17005	51	35
1995	Meaford	695	695	1195	5	15243	47	28
1995	Chesley	695	695	1195	5	15243	47	10
1995	Bervie	695	695	1195	5	15243	47	0

Figure 8.4 Foliar Injury to White Bean in Ontario and Short-Term SUM60s (1995)



The following conclusions were drawn from the 1995 white bean foliar injury-ozone air quality assessment (detailed statistical analyses are presented in the Report of the Vegetation Objective Working Group (Multistakeholder NO_x/VOC Science Program, 1997, VOWG):

- the three-month SUM60 (ppb-h) for the period June-August was unrelated to the severity of foliar injury ($p = 0.134$);
- the number of exceedances of the existing Canadian air quality objective for ozone during the three-month period of June-August was unrelated to the severity of foliar injury ($p = 0.244$);
- the number of exceedances of the existing air quality objective of 82 ppb during the previous 20 days (from the date of injury assessment) was unrelated to the severity of foliar injury ($p = 0.318$);
- of the three short-term cumulative SUM60 indices, the 3-day index performed the best ($p = 0.021$; this was followed by the 5-day and 1-day indices ($p = 0.072$ and 0.147, respectively.

Based on the foregoing analysis for 1995, a decision was made to reassess the foliar injury assessments of previous years, which, although not as extensive as in 1995, have been ongoing in southwestern Ontario over the past decade (1985-95). The data from this assessment are shown in Table 8.14, (details of the statistical analysis are presented in the Report of the Vegetation Objective Working Group (Multistakeholder NO_x/VOC Science Program, 1997, VOWG). Figure 8.5 (A-D) displays the relationship between the short-term cumulative indices (1- and 3-day SUM60s, scatter plots A and B) as well as with the maximum 1-hour ozone concentration (scatter plot C) and exceedances of the existing 1-hour ozone concentration of 82 ppb (scatter plot D) during the 20-day period preceding injury assessment in each of the 11 years. An analysis of the 5-day SUM60 is unfortunately not available.

Table 8.14 Assessment of potential short-term indices based on foliar injury to white bean in Ontario (1985-1995)

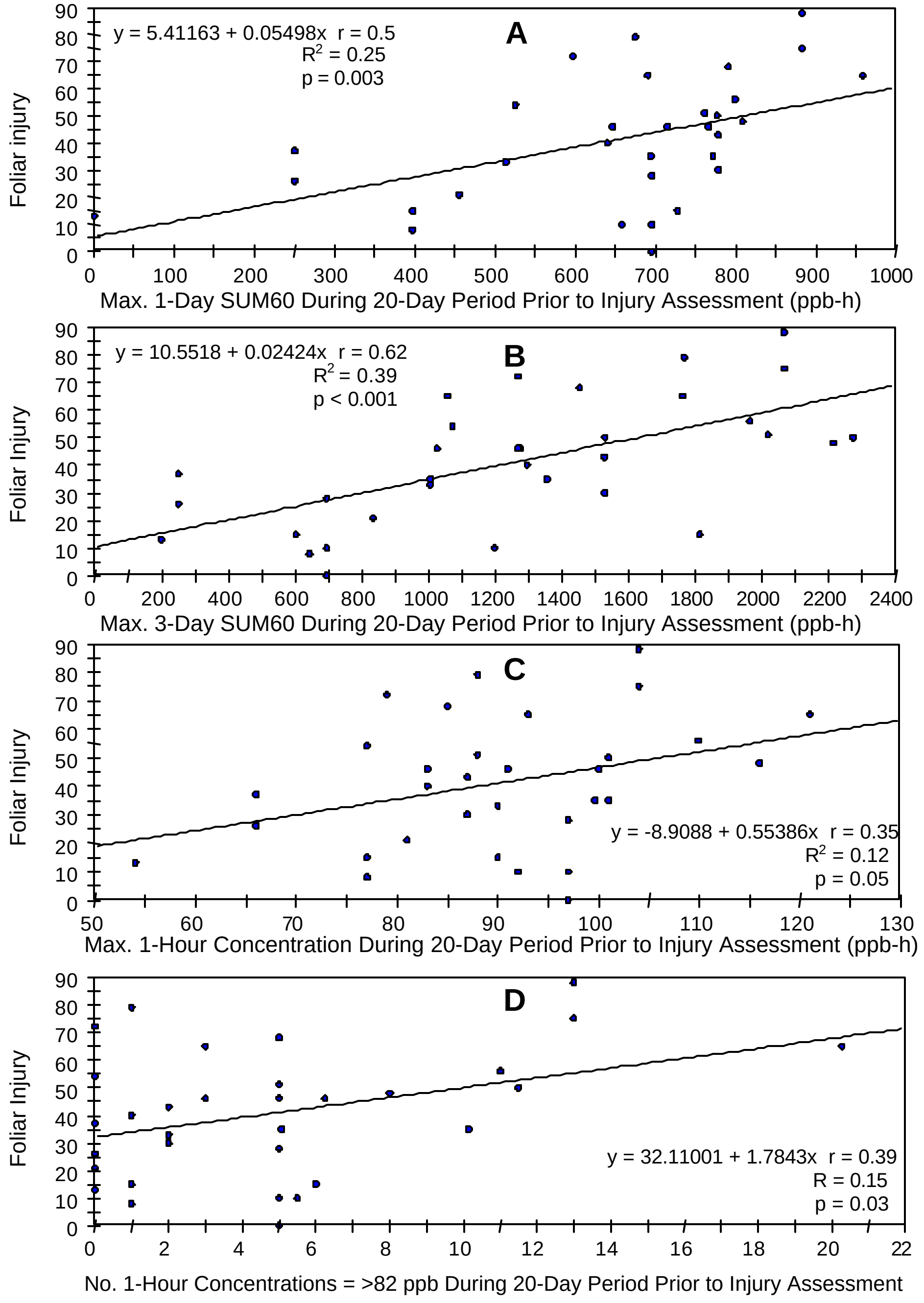
Year	Crop Location	Previous 20-Day Period												Foliar Injury Index (0-100)
		Max. 1-day SUM60 (ppb-h)	No. of 1-day SUM60 = > 300 (days)	No. of 1-day SUM60 = > 400 (days)	No. of 1-day SUM60 = > 500 (days)	No. of 1-day SUM60 = > 700 (days)	Max. 3-day SUM60 (ppb-h)	No. of 3-day SUM60 = > 500 (days)	No. of 3-day SUM60 = > 700 (days)	No. of 3-day SUM60 = > 900 (days)	No. of 3-day SUM60 = > 1100 (days)	Max. 1-h (ppb)	No. Hrs =>82 (ppb)	
1995	Elora	766	5	3	3	1	1275	10	5	3	2	83	3	46
1995	Harrow	959	8	7	6	3	1762	15	15	15	10	121	20	65
1995	Ridgetowr	772	5	4	4	2	1356	9	9	9	5	101	10	35
1995	Huron Park	691	4	2	1	0	1055	4	2	2	0	93	3	65
1995	Brussels	715	5	3	2	0	1024	7	3	3	2	100	6	46
1995	Shetland	695	2	2	1	1	1005	5	4	2	0	100	5	35
1995	Meaford	695	4	3	2	0	695	6	0	0	0	97	5	28
1995	Chesley	695	4	3	2	0	695	6	0	0	0	97	5	10
1995	Bervie	695	4	3	2	0	695	6	0	0	0	97	5	0
1994	Elora	762	4	4	4	1	2017	8	4	4	3	88	5	51
1994	Huron Park	675	4	4	3	0	1765	8	5	3	3	88	1	79
1993	Harrow	640	5	4	2	0	1294	8	8	2	1	83	1	40
1993	Ridgetowr	526	3	2	1	0	1072	5	4	2	1	77	0	54
1993	Huron Park	455	2	1	0	0	834	3	3	0	0	81	0	21
1992	Harrow	597	3	3	2	0	1269	6	3	2	1	79	0	72
1992	Huron Park	728	5	5	3	1	1812	7	4	4	4	90	6	15
1991	Harrow	778	6	3	1	1	1527	8	6	4	2	87	2	30
1991	Ridgetowr	778	6	3	1	1	1527	8	6	4	2	87	2	43
1991	Huron Park	799	8	6	5	2	1962	7	7	5	4	110	11	56
1990	Harrow	883	8	5	4	2	2065	11	10	6	5	104	13	88
1990	Ridgetowr	883	8	5	4	2	2065	11	10	6	5	104	13	75
1990	Huron Park	791	5	3	2	1	1453	10	5	4	3	85	5	68
1987	Ridgetowr	809	6	5	5	2	2215	10	6	5	5	116	8	48
1987*	Huron Park	827	4	4	4	4	2330	8	5	5	3	105	15	29

Table 8.14 (cont'd) Assessment of potential short-term indices based on foliar injury to white bean in Ontario (1985-1995)

Year	Crop Location	Previous 20-Day Period												Foliar Injury Index
		Max. 1-day SUM60 (ppb-h)	No. of 1-day SUM60 = > 300 (days)	No. of 1-day SUM60 = > 400 (days)	No. of 1-day SUM60 = > 500 (days)	No. of 1-day SUM60 = > 700 (days)	Max. 3-day SUM60 (ppb-h)	No. of 3-day SUM60 = > 500 (days)	No. of 3-day SUM60 = > 700 (days)	No. of 3-day SUM60 = > 900 (days)	No. of 3-day SUM60 = > 1100 (days)	Max. 1-h (ppb)	No. Hrs =>82 (ppb)	(0-100)
1987	Kippen	777	3	3	3	3	1529	7	4	3	2	101	12	50
1987	Brussels	777	5	3	5	3	2273	9	6	5	4	101	12	50
1986*	Harrow	0	0	0	0	0	199	0	0	0	0	54	0	53
1986	Ridgetown	0	0	0	0	0	199	0	0	0	0	54	0	13
1986	Huron Park	514	3	2	1	0	1004	6	3	2	0	90	2	33
1986	Kippen	397	2	1	1	0	642	3	2	1	0	77	1	8
1986	Brussels	397	2	1	1	0	302	3	2	1	0	77	1	15
1985	Harrow	250	0	0	0	0	250	0	0	0	0	66	0	26
1985	Ridgetown	250	0	0	0	0	250	0	0	0	0	66	0	37
1985	Huron Park	646	3	3	3	0	1268	7	5	3	2	91	5	46
1985	Brussels	659	4	3	3	0	1198	7	5	4	2	92	6	10

* Two outlier results removed for regression analysis (Harrow 1986 and Huron Park 1987).

Figure 8.5: Foliar injury to white bean in Ontario and short-term SUM60 and hourly ozone (1985-95)



This analysis confirmed the 1995 findings, in which the 3-day SUM60 index performed the best as an indicator of air quality associated with foliar injury development ($p < 0.001$ and an R^2 of 39%); however, statistically significant relationships also were recorded for the 1-day SUM60 ($p < 0.01$) and the number of exceedances of the 1-hour objective of 82 ppb ($p = 0.03$), although the latter two indices attributed a considerably smaller percentage of injury severity to ozone, with R^2 values of 25 and 15%, respectively.

In summary, the foliar injury to white bean crops in southwestern Ontario was found to be very significantly related to cumulative ozone exposure over a three-day period during the three week (20-day) period prior to injury assessment as measured by the 3-day SUM60 index. The next best descriptor of foliar injury during this 20-day period was a one-day SUM60. Both were clearly superior (in terms of the relationship between injury severity and ozone air quality) to a count of 1-hour exceedances of the existing ozone objective of 82 ppb and from a biological perspective, this was not unexpected, given the cumulative manner in which ozone is taken up by plant foliage and metabolized. It is clearly a more biologically relevant scenario than is the number of exceedances of a certain 1-hour threshold (e.g. a level of 82 ppb) which implies that plants suddenly become sensitive and develop injury after exposure to very short peak exposures. However, the longer averaging period for the SUM60 index does not capture all of the biologcally relevant aspects of plant exposure to pollutants, though the SUM60 form itself performed reasonably well.

These findings are consistent with the early publications dealing with ozone injury to this crop (Weaver & Jackson, 1968; Haas, 1970, and Curtis et al., 1975) and point to the need for a short-term, episode-based indicator of ozone air quality.

8.2.5 Exposure Response Relationships for Acute Effects

The 1995 white bean foliar injury – ozone air quality study referred to in the previous section, besides assessing the relative value of alternative exposure indices, also shed some light on exposure-response relationships. Figure 8.4B demonstrates the relationship between white bean foliar injury, measured using the foliar injury index described earlier, and ozone exposure, measured with the 3-day SUM60. A trace level of foliar injury (foliar injury index score of 1-20) is the lowest level of injury that can be reliably quantified and is therefore a suitable assessment endpoint. Based on this analysis, the following conclusions can be made:

- a 3-day SUM60 of 500-700 ppb-h is associated with a trace injury level (foliar injury index less than or equal to 20)

Therefore, based on the 1995 white bean analysis, a LOAEL in the range of 500-700 ppb-h (3-day SUM60) is identified.

Further evaluation of the relationship between foliar injury severity on white beans and the 3-day SUM60 was done for the period 1985 - 1995. In the previous 1995 assessment, the maximum 3-day SUM60 during the 20-day period prior to assessment was selected for evaluation against foliar injury severity. In the second phase of this assessment, the relationship between the 3-day

SUM60 was explored on an exceedance basis in an attempt to determine the most appropriate concentration to provide short-term protection. This analysis of the 1985-95 white bean injury assessment included the following scenario:

- number of exceedances of 3-day SUM60 values of 500, 700, 900 and 1,100 ppb-h during the previous 20-day period.

The results of the statistical analysis are plotted in Figure 8.6. Again, detailed statistical analyses can be found in the Report of the Vegetation Working Group (Multistakeholder NO_x/VOC Science Program, 1997, VOWG). The following conclusions were drawn from this analysis:

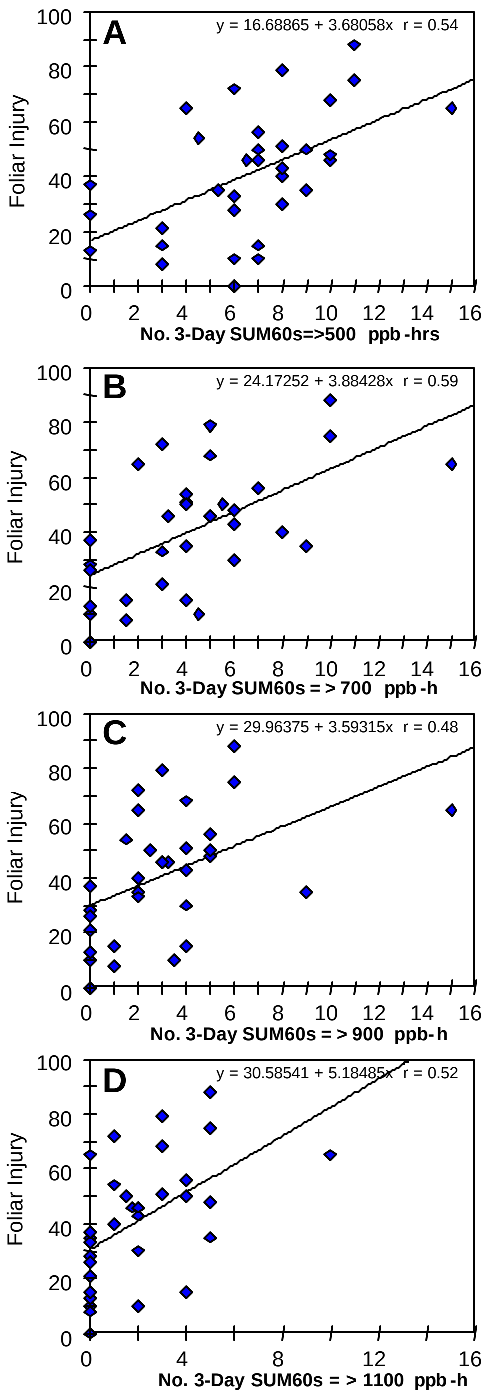
- the relationship between exceedances of a range of candidate 3-day SUM60 levels and foliar injury was highest at 700 ppb-h (scatter plot B) followed by 500 ppb-h (scatter plot A);
- the evaluation of a short-term index from an exceedance basis reveals considerable variability in the relationship with foliar injury; however, from the scatter plots, it is apparent that as the level of the 3-day SUM60 is increased from 500-1,100 ppb-h, the number of cases where greater than a trace level of injury (Foliar Injury Index > 20) occurs, with zero exceedances of the candidate SUM60 value, also increases; this provides support for a 3-day SUM60 value at the lower end of the proposed range (i.e., 500-700 ppb-h).

Therefore, a LOAEL range for trace foliar injury is identified as follows:

- A rolling 3-day SUM60 during the daily 12-hour daylight period (08:00-19:59) for the months of April-September in the range of 500 - 700 ppb-h.

- Although both the form of the 3-day SUM60 index and the LOAEL range for acute effects have been developed on the basis of analysis of only two crops (radish and white bean) in this assessment, both of these plants are known to be sensitive to foliar injury development and to be significantly impacted as a direct result of the foliar injury.

Figure 8.6 Relationship Between Exceedances of the 3-day SUM60 and Foliar Injury to White Bean in Ontario (1985-95)



8.3 EXPOSURE ASSESSMENT FOR VEGETATION

Chapter 5 (section 5.3) of this document described the monitoring network for ground-level ozone across Canada and ambient concentrations in a regional context. As mentioned in Chapter 5, there are far more urban monitoring sites than rural or remote sites. The resulting lack of ambient data for non-urban areas is a limitation to any exposure assessment for Canadian agricultural crops or forests to ground-level ozone.

Ground-level ozone is monitored on a continuous basis and data archived as one hour averages. For the purpose of assessing ground-level ozone exposure to vegetation the data from non-urban sites are used to calculate three-month and three-day SUM60 values for rural and forested sites in Canada during 1985-93. This is summarized in Figures 8.7 and 8.8. The percentile data for these sites are shown in Table 8.15.

Figure 8.7 Frequency of 3-Month SUM60 Values at Rural and Forest Sites in Canada (1985-1993)

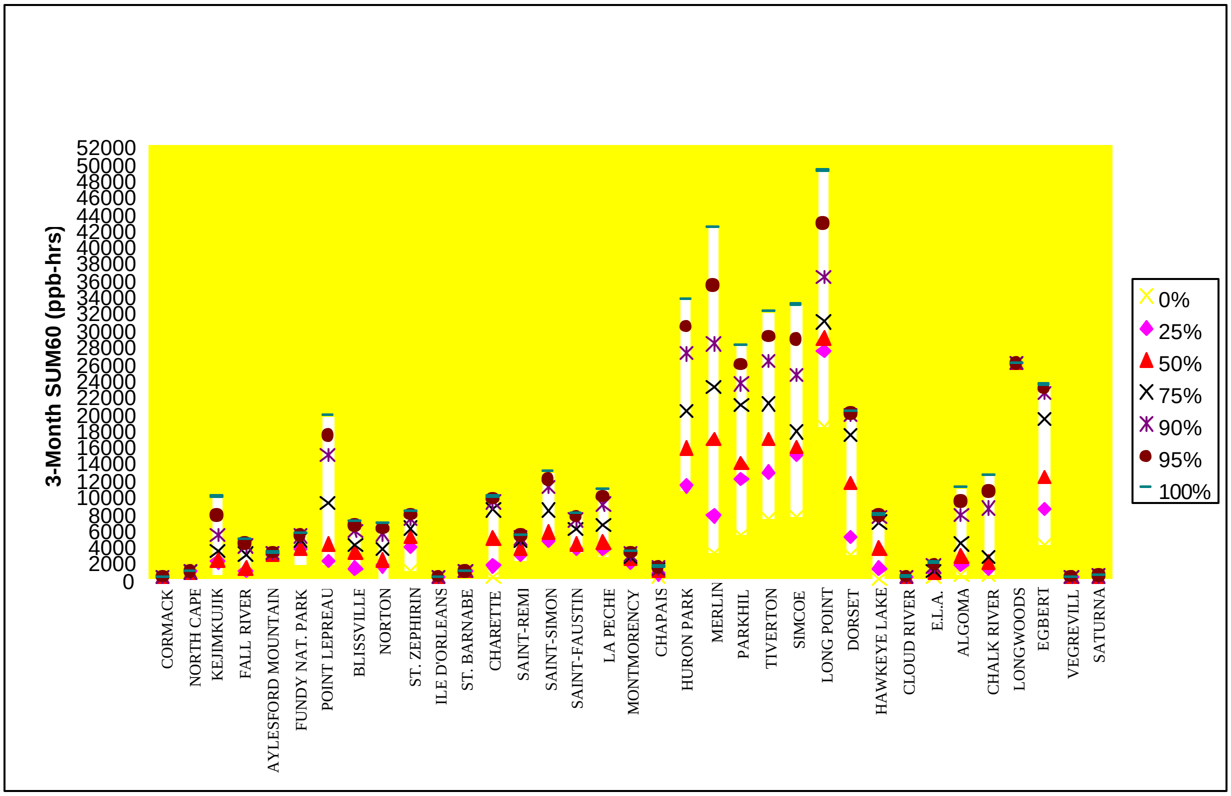


Figure 8.8 Frequency profile of 3-day SUM60 values at rural and forest sites in Canada (1985-1993)

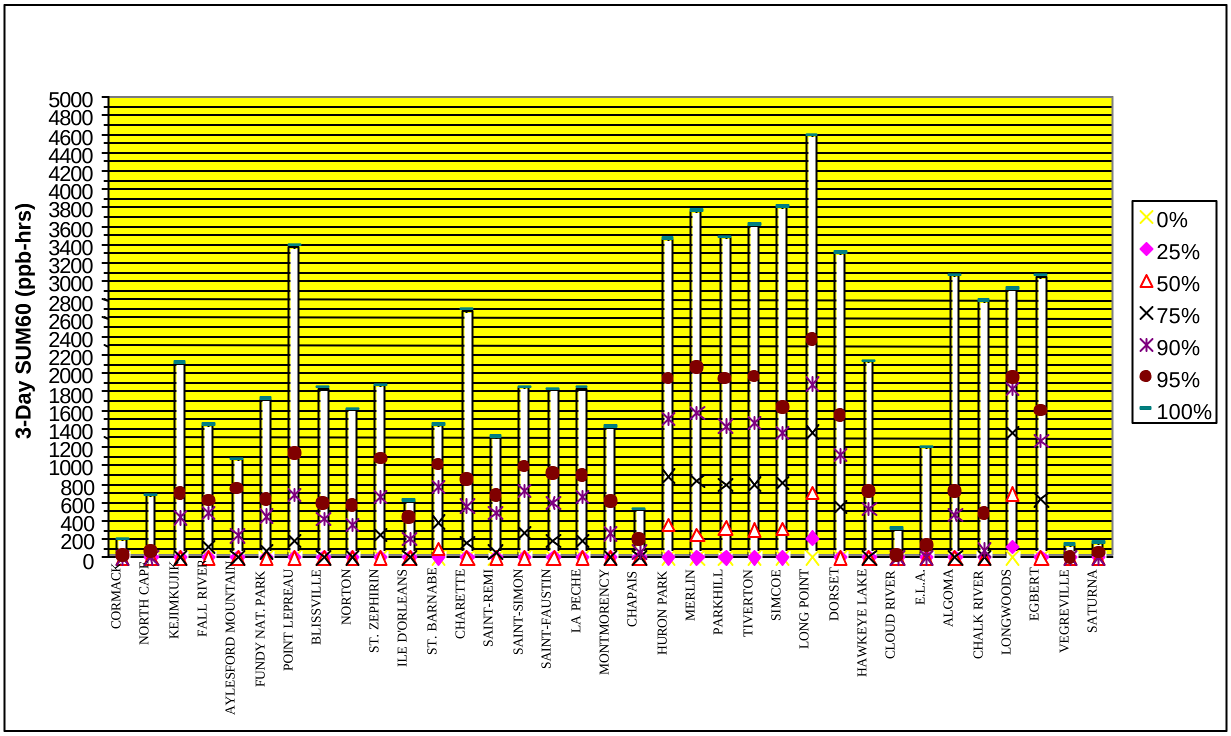


Table 8.15 Frequency profile for 3-day and 3-month SUM60 values at rural/forest sites in Canada (1985-1993)

NAPS ID	Location	Frequency Profile - 3-DaySUM60							Frequency Profile - 3-Month (June-August) SUM60						
		0%	25%	50%	75%	90%	95%	100%	0%	25%	50%	75%	90%	95%	100%
10201	CORMACK, NF	0	0	0	0	0	15	200	120	123	125	133	138	140	141
20201	NORTH CAPE, PEI	0	0	0	0	0	66	679	805	805	805	805	805	805	805
30501	KEJIMKUJIK, NS	0	0	0	0	430	694	2117	335	1985	2223	3278	5245	7541	9836
30601	FALL RIVER, NS	0	0	0	122	485	622	1442	587	897	1208	2904	3922	4261	4600
30701	AYLESFORD MOUNTAIN, NS	0	0	0	0	237	751	1064	2717	2820	2922	3024	3086	3106	3127
40401	FUNDY NAT. PARK, NB	0	0	0	61	451	627	1729	1649	3564	3637	4658	5076	5215	5354
40501	POINT LEPREAU, NB	0	0	0	180	679	1135	3384	1506	2118	4161	9016	14845	17164	19484
40601	BLISSVILLE, NB	0	0	0	0	412	580	1840	795	1197	3211	4036	5699	6254	6808
40701	NORTON, NB	0	0	0	0	349	563	1613	0	1494	2207	3465	5345	5971	6598
51501	ST. ZEPHIRIN, QC	0	0	0	252	660	1077	1870	952	3737	4996	5998	7206	7608	8011
51601	ILE D'ORLEANS, QC	0	0	0	0	206	439	621	160	160	160	160	160	160	160
51701	ST. BARNABE, QC	0	0	93	386	770	1015	1441	856	856	856	856	856	856	856
52001	CHARETTE, QC	0	0	0	151	563	850	2690	211	1508	4827	8252	9222	9545	9868
52101	SAINT-REMI, QC	0	0	0	60	487	673	1312	2130	2896	3662	4429	4888	5042	5195
52201	SAINT-SIMON, QC	0	0	0	270	720	993	1850	4200	4419	5568	8173	10926	11843	12760
52301	SAINT-FAUSTIN, QC	0	0	0	185	590	910	1830	3130	3611	4091	5949	7064	7436	7807
52401	LA PECHE, QC	0	0	0	180	660	889	1840	2529	3537	4406	6360	8915	9766	10618
54001	MONTMORENCY, QC	0	0	0	0	258	615	1428	1586	1829	2423	2533	2890	3057	3224

Table 8.15 (cont'd) Frequency profile for 3-day and 3-month SUM60 values at rural/forest sites in Canada (1985-1993)

NAPS ID	Location	Frequency Profile - 3-DaySUM60							Frequency Profile - 3-Month (June-August) SUM60						
		0%	25%	50%	75%	90%	95%	100%	0%	25%	50%	75%	90%	95%	100%
54201	CHAPAIS, QC	0	0	0	0	60	199	530	313	586	859	1132	1296	1351	1405
62101	HURON PARK, ON	0	0	351	884	1505	1940	3463	10524	11120	15630	20038	26977	30234	33491
62201	MERLIN, ON	0	0	245	837	1566	2064	3770	2942	7518	16728	22935	28144	35144	42143
62401	PARKHILL, ON	0	0	320	790	1429	1948	3473	5250	11963	13918	20766	23364	25688	28012
62501	TIVERTON, ON	0	0	304	797	1465	1967	3620	7103	12769	16701	20956	26100	29043	31987
62601	SIMCOE, ON	0	0	308	816	1353	1628	3810	7433	14821	15799	17601	24385	28623	32862
62701	LONG POINT,ON	0	210	706	1361	1885	2372	4580	18271	27365	28877	30784	36140	42546	48951
63301	DORSET, ON	0	0	0	556	1110	1536	3312	2754	4961	11474	17181	19560	19801	20041
63401	HAWKEYE LAKE, ON	0	0	0	0	530	714	2132	0	1214	3653	6732	7368	7495	7622
63901	CLOUD RIVER, ON	0	0	0	0	0	27	313	183	183	183	183	183	183	183
64001	E.L.A., ON	0	0	0	0	0	125	1195	260	665	824	911	1504	1702	1900
64101	ALGOMA, ON	0	0	0	0	472	716	3062	517	1659	2680	4182	7708	9273	10839
64201	CHALK RIVER, ON	0	0	0	0	82	477	2788	434	1080	1932	2615	8472	10425	12377
64301	LONGWOODS, ON	0	123	692	1357	1833	1961	2923	25817	25817	25817	25817	25817	25817	25817
64401	EGBERT, ON	0	0	0	632	1267	1592	3058	3926	8297	12155	19066	22215	22747	23279
90901	VEGREVILLE, AB	0	0	0	0	0	0	145	148	148	148	148	148	148	148
102001	SATURNA. BC	0	0	0	0	0	61	164	126	146	166	285	356	379	403

8.4 RESEARCH NEEDS

There are several significant areas where additional research would provide much needed certainty for the establishment of vegetation based air quality criteria for Canada. Some of these were summarized recently by Heck and Cowling (1997) following a workshop of vegetation experts in early 1996. From a Canadian point of view, the more important areas include:

- the implementation of a fully monitored experimental open-top chamber program for crop and tree species throughout Canada, to develop dose-response relationships for Canadian species;
- review and development of vegetation exposure indices that best reflect the biologically relevant aspects of ozone exposure using Canadian experimental data, from point above;
- detailed exposure assessment to determine the severity of current impacts and anticipated risks to Canadian agricultural and tree species;
- the continued evaluation of factors influencing vegetation response to ozone, particularly those that relate to the use of air quality data as surrogates of ozone exposure at locations remote from the vegetative canopy (i.e., study of flux of ozone to plant and ecosystem canopies);
- the study of interactive effects of ozone with other plant stressors, including other oxidants, and co-occurring regional pollutants, insects, disease, drought stress, soil nutrition and factors involved in climate change;
- the investigation of how adverse effects of ozone occurring at the cellular level can be interpreted in terms of foliar or canopy-level impacts and, ultimately, effects at the ecosystem level; and
- the VOWG analysis also pointed to the need for much improved ozone-monitoring coverage in many rural and forested areas of Canada and the establishment of an experimental monitoring program to investigate the most appropriate monitoring location relative to canopy position/level.

8.5 SUMMARY

For chronic effects, LOAEL ranges were identified for both agricultural and tree species, and a LOAEL range was also identified for acute impacts on agricultural species. These were:

- 3 month SUM60 LOAEL range, at the 10% biomass loss level, of 5,900 to 7,400 ppb-h for agricultural species (see Table 8.10)
- 3 month SUM60 LOAEL range, at the 10% biomass loss level, of 4,400 to 6,600 ppb hrs for tree species (see Table 8.11)
- 3 day SUM60 LOAEL range, at the trace foliar injury level, of 500 to 700 ppb hrs for agricultural species

Given the available experimental data it was determined that the uncertainties in the data and lack of quantitative Canadian dose-response data were too great to further narrow the range and identify single numerical LOAELs for agricultural or tree species. It is recommended that when experimental data do become available that efforts be focussed on developing LOAELS for vegetation classes (e.g.: cereals, pulses, legumes, vegetables, coniferous trees, deciduous trees). The inter species variability is anticipated to be too great for the determination of a single valid LOAEL.

For the purposes of assessing ozone impacts to vegetation impacts in Canada the reader is referred to Tables 8.9 and 8.11 which present the best available species specific estimates of ozone levels at which reduced yield or biomass loss may occur.

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