# <u>The Effects of Tropospheric Ozone Pollution on Forests</u>

**FRST 497 Graduating Essay**

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April 9, 2012

## Abstract

Ozone is a significant risk factor to the health of the forest ecosystem. The level of this atmospheric oxidant has increased in regions of the US and Canada, highlighting the importance of understanding its impact on agricultural crops and forest tree health at large. However, the link between the occurrence of ozone and forest damage is not firmly established because of limited knowledge on the acclimation of growing trees to ozone. The insufficiency of knowledge stems from challenges in conducting accurate and thorough assessments of ozone injury on the forest. Evidence from experiments show that ozone can impose stress on trees, and it can affect forest tree metabolism by interfering with carbon dynamics, which are associated with photosynthesis, respiration, and carbon allocation.

In this paper, the phytotoxic effects of ozone are described by first providing background information on the formation and calculation of ozone, followed by a discussion of the underlying mechanism and symptoms of ozone damage. Case studies from Southern California and Switzerland are also included to highlight the relationships between ozone concentration, drought, and tree species. Lastly, the difficulties in conducting ozone studies are detailed, along with the serious implications of ozone damage, such as the loss of genetic diversity within the forest.


Key words: Ozone concentration, stomata, photosynthesis, ozone injury, tropospheric ozone

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## Introduction

The sustainability of the forest plays a critical role in climate change because the characteristics of the forest can lead to either carbon sequesters or carbon emitter. The reaction of nitrogen oxide and volatile organic compounds has become the greatest concern for concentration levels in the tropospheric ozone ($O_3$). Although pollutants produced from heavy industry have shown a decline, $O_3$ concentrations have shown increases (Matyssek & Innes, 1999). The U.S. Environmental Protection Agency has announced that the $O_3$ pollution in the Eastern United States is considered the greatest threat to vegetation (Edwards, Huber & Wood, 2003).

Recent studies have shown that tropospheric $O_3$ pollution can impact the forest stand and tree level. In Europe, the examination of visible injury in woody plants has led to the understanding of the risks associated with $O_3$ on forest trees and forest ecosystems (Matyssek & Innes, 1999). In the States, evidence has revealed that "$O_3$ exposure tends to increase with elevation" and can result in "physiological damage to forest vegetation" in different regions (Krzyzanowski, McKendry, & Innes, 2005). Damage observed includes both "foliar damage and changes in forest composition" in the areas of study (Krzyzanowski et al., 2005). It has also been suggested that the effects of $O_3$ exposure on the physiological damage of trees are linked to the stomata function (Zhang, Ferdinand, Vanderheyden, Skelly & Innes, 2001).

## Hypothesis

Prolonged increase in tropospheric ozone combined with interchanging drought and wet soil conditions will result in foliar injury, negatively impacting forest health.

# Objective

The objective of this study is to discuss the effects increased tropospheric $O_3$ pollution has on forests, and even on particular tree species. This requires exploring the formation of $O_3$, identifying the symptoms of the damage on the forest, and examining the interplay between $O_3$ and other environmental factors that contribute to foliage damage.

# Background Knowledge

## History

The impacts of tropospheric $O_3$ were first observed in 1952 in the Eastern United States, where damage appeared on several plant species. The damage was first described as “weather fleck” on cigar leaves, displaying “straw-colored flecks and lesions” and leading to symptoms of chlorosis and wilting (Treshow & Anderson, 1989). Later, the US Forest Service observed similar symptoms of “premature loss of older leaves, yellowing and browning of current year needles, stippling or mottling of foliage, gradual reduction of growth and striking variation in sensitivity among individual trees” which was then known as the “X” disease (Treshow & Anderson, 1989). The greatest $O_3$-injury occurred in the eastern white pine with symptoms appearing in almost 23% of the stands in the southern Appalachian Mountains (Treshow & Anderson, 1989). This resulted in the need to examine the relationship between $O_3$ concentration exposure and the effects on different tree species.

## Formation of Ozone Concentration

The concentration of $O_3$ is controlled by the chemical compounds within the air, the time of day, and the local meteorology conditions (Chaikowsky, 2001). Ozone has been characterized as a secondary pollutant created by the reaction between nitrogen oxides ($NO_x$) and volatile organic compounds (VOCs) in the presence of sunlight (Chaikowsky, 2001). $NO_x$ are formed from combustion reactions between NO and $NO_2$, which can be generated from activities including “transportation, thermal electrical power plants, industrial activities and waste incineration" (Chaikowsky, 2001). VOCs, on the other hand, are made of hydrogen and carbon atoms from both biogenic and anthropogenic sources, such as industrial and transportation processes (Chaikowsky, 2001). When VOCs react with sunlight, they form peroxy radicals that react with NO to form nitric oxides, which are the fundamental molecules for $O_3$ formation (Chaikowsky, 2001).

| | | | | |
|---|---|---|---|---|
| $NO_2$ contributes to | $NO_2$ + sunlight | → | NO + O | |
| | O + $O_2$ | → | $O_3$ | ozone formation |
| while NO acts to | NO + $O_3$ | → | $NO_2$ + $O_2$ | destroy ozone |

As $NO_2$ reacts with ultraviolet radiation (UV), it produces NO and O. The singlet O then reacts with $O_2$ to produce $O_3$. The reaction is considered rate limited as NO can assist in the destruction of $O_3$ molecules, therefore breaking down the amount of $O_3$ concentration. However, the amount of NO present in the atmosphere is influenced by the amount of reactive hydrocarbons produced from gasoline and auto exhaust. As reactive hydrocarbon bonds with NO, it greatly reduces the concentration of NO, which leads to an increase in the concentration of $O_3$ (Temple, Bytnerowicz, Fenn & Poth, 2005). As a result, the concentration of $O_3$ is dependent on the available $NO_2$ and NO in the atmosphere.

The time of day can also affect $O_3$ concentration. As mentioned above, the concentration of $O_3$ is affected by photochemical reactions, which start with the amount of solar radiation received at the atmospheric level. For example, during morning rush hour, concentration of $O_3$ has been documented to be low. However, as solar radiation gradually increases during the day, it triggers photochemical $O_3$ production, which then elevates the $O_3$ concentration (Temple et al., 2005).

Local meteorological conditions can also influence the concentration of $O_3$. In California, the onshore breeze carries the polluted air mass from west to east, creating an increasing gradient of $O_3$ (Temple et al., 2005). Furthermore, the height of "inversion layers also increases from west to east as elevations increase" and as the temperature increases (Temple et al., 2005). During the day, $O_3$ concentrations on mountain slopes usually rise over mountain ridges as the heat moves the polluted air upwards (Temple et al., 2005). Ozone concentration can also increase as the upper tropospheric zone is vertically mixed and transported downward (Chaikowsky, 2001). As temperature drops, it results in a lack of vertical mixing, keeping the $O_3$ concentration near the surface. As a result, “high concentrations of $O_3$ persist in the evening and early morning hours in forested areas of the mountains, while $O_3$ concentrations in the valleys typically decrease rapidly as the sun sets” (Temple et al., 2005).

The combinations of the factors have shown to affect the $O_3$ concentration levels. It has been noted that the $O_3$ concentrations are greatest under the following conditions: “high NO emissions, low solar radiation during the night, limited VOCs near $NO_x$ sources, and limited mixing in a $NO_x$ rich environment” (Chaikowsky, 2001).

## Calculations of Ozone Concentration:

To examine the effects tropospheric $O_3$ has on forests, the correlation between the cumulative amount of $O_3$ in the air and the resulting damage has to be determined. Different methods have been conducted to measure the cumulative amount of $O_3$ exposure to the forest. In this report, $O_3$ data is examined in the context of the SUM60 and AOT40 indices. SUM60 is defined as the “total sum of concentration at or above 60 ppb between 0800 and 1959h” over a 3-month growing period (Chaikowsky 2001). The AOT40 is based on the “seasonal censored sum of hourly concentration above a threshold level. The AOT40 value is calculated by subtracting 40 ppb from each hourly concentration that exceeds 40 ppb during daylight hours (0700h-2100h)” (Chaikowsky, 2001). Research papers and case studies conducted in Switzerland and Southern California have also been examined to further explore the impact $O_3$ has on the forest and the possible mechanisms leading to the damage.

## Understanding the Risks of Ozone

Increasing concern has been raised over the impact of $O_3$ over the past few decades, and so stations were built to measure the $O_3$ concentration in urban and suburban areas. On the scale of individual trees, ozone can significantly inhibit the growth and reproduction of trees, the severity of which depends on the sensitivity of each tree (Matyssek & Innes, 1999). On a large scale, elevated levels of $O_3$ can endanger the health of the ecosystem. This is one of the drastic consequences of increasing $O_3$ concentration, whereby genotypes of sensitive trees are lost in the long-run, reducing the genetic diversity of the forest. From a practical point of view, this can reduce the resistance of the forest population to stress, making the forest more susceptible to injury. Given the significant impact $O_3$ brings on the ecosystem, it is critical to understand the mechanism by which $O_3$ damages the trees and to recognize the physical signs that indicate such damage.

### A. Underlying Mechanism of Ozone Damage

The concentrations in the tropospheric $O_3$ have shown to affect the behavior of stomata. The stomata serve a vital role, as they act as the primary gateways for gases to enter the leaves (Temple et al., 2005). Stomata conductance is defined as the rate at which gas exchange takes place and can be affected by "physiological and environmental factors", such as "light intensity, temperature, relative humidity, and soil moisture," which in turn affects the rate and the concentration of $O_3$ entering the stomata (Temple et al., 2005).

As a result of exposure to $O_3$, the stomata conductance and photosynthetic ability of the leaves are both affected. When exposed to $O_3$ concentrations on a long-term basis, stomata can develop a sluggish response to light, forcing them to remain open at night (Paoletti et al., 2007). When the stomata remain open for long periods, $O_3$ enters the stomata cavity, oxidizes the mesophyll cell wall, increases cell wall permeability and makes the cells more vulnerable to injury (Krzyzanowski et al, 2005). This creates a feedback loop that promotes further entry of ozone molecules, since the increased permeability and degradation of the cell wall creates more exposure to $O_3$. Once the $O_3$ concentration exceeds the capacity of cellular detoxification and the cell's repair mechanisms, membrane functions are impaired and biochemical activities start to break down (Temple et al., 2005). This damage culminates in degraded cell walls and plasmalemma (Matyssek & Innes, 1999). The damage to the plasmalemma may triggers defense mechanisms similar to pathogenic infections, leading to cellular apoptosis and chloroplast degradation (Matyssek & Innes, 1999). The oxidation and signaling of apoptosis in the mesophyll cause the loss of premature leaves. As the leaf cells become more prone to injury through oxidation, the trees growth will be inhibited.

Not only are the cell walls damaged as a result of long-term $O_3$ exposure, but also the photosynthetic rates are increased. With a sluggish stomata response to light, small exposures of photosynthetic active radiation may increase the trees' sensitivity to $O_3$ (Zhang et al., 2001). Since the stomata remains open longer, more photosynthetic activity can take place. The increase in photosynthesis rate along with a decrease in transpiration rate can result in a reduction in the trees' water-use efficiency (Matyssek & Innes, 1999). The tipping point is reached when the tree is no longer capable of supplying the nutrients required for the increased photosynthetic activity. At this point, leaf abscission can take place; if severe, the health of the tree is compromised. This mechanism, combined with the finding that $O_3$ concentration has been observed to be sometimes higher at night than during the day, greatly compounds the damage brought by increased stomata conductance (Zhang et al., 2001).

Long-term exposure to $O_3$ concentration can bring about a cascade of events that begins with a sluggish stomata response to light, oxidation and degradation of cell walls, as well as increased photosynthetic ability. In the end, once the leaves have sustained enough injury, chloroplasts are also exposed to oxidation, thereby reducing the rate of photosynthesis. The total amount of carbon fixed over the period of growth is significantly reduced by the decrease in the level of photosynthetic activity and the amount of photosynthetic tissue. In plants exposed to high concentrations of $O_3$, the lower amount of carbon available will yield fewer carbohydrates needed for the tree's repair mechanism, growth, reproduction, and its defense from natural stressors (Temple et al., 2005).

## B. Symptoms

The effects of $O_3$ concentration on the activities within the leaves can only be examined using specific equipment. As a result, there is a need to determine the damage that $O_3$ concentration has on a tree's health. Studies have been conducted to understand the symptoms of trees resulting from $O_3$-induced damage. Visible signs of $O_3$-induced damage are usually observed on the upper leaf surface, indicating a "permanent loss of photosynthetic capacity in the chloroplasts of the underlying cells" (Temple et al., 2005). As the $O_3$ concentration level remains static and the damage accumulates, leaves exhibit signs of premature aging, including "upper surface stipple, leaf reddening, and premature senescence" (Skelly, Innes, Snyder, Savage, Hug, Landolt & Bleuler, 1997). It has been documented that older leaves, which have been exposed to $O_3$ concentration the longest, exhibited the most foliar injury (VanderHeyden, Skelly, Innes, Hug, Zhang, Landolt & Bleuler, 2001).

Studies conducted in Switzerland, southern Spain and in California have indicated that different species of trees show different signs of injury. Broad-leaved plants have shown damage through a "chlorotic stipple over the leaf surface," particularly near the leaf veins and veinlet (Temple et al., 2005). The stipples on broad-leaves have shown colors of "red, brown, purple or black" when exposed to sunlight (Matyssek & Innes, 1999). Meanwhile conifer injuries are more diffuse, leading to an $O_3$-injury pattern of chlorotic mottle (Temple et al., 2005). Conifer species, pine in particular, have shown an increase in leaf litter when exposed to high concentrations of $O_3$, resulting in "accelerated senescence and abscission of $O_3$-injured pine needles (Temple et al., 2005).

The age of the leaves, as well as the time of year, also plays a role in the symptoms observed. In southern Switzerland, young leaves have been observed to have damage on leaf margins and tips, while older leaves tends to develop damage near the base (Skelly et al., 1997). At the end of the growing season, sensitive species have shown damage on their entire leaves as they tend to be older and are exposed to elevated $O_3$ levels the longest (Skelly et al., 1997).

# Case Studies

## Southern California

The effects of $O_3$ on mixed coniferous forests, especially ponderosa (*Pinus ponderosa*) and Jeffrey pines, in Southern California have been examined and analyzed. Due to the unique characteristics of the "topography, climatological and social characteristics of Los Angeles", the area has shown to have one of the "highest levels of oxidant air pollution" surrounding the mixed conifer forests found in the mountains of Southern California (Temple et al., 2005). The first indicator of $O_3$-induced damage emerged in 1953 when *P. ponderosa* exhibited signs of "needle chlorosis, necrosis, and premature needle abscission" (Temple et al., 2005). In 1960, it was postulated that the death of over 25 percent of the pines can be related to $O_3$-injury. As the pines become injured, they produce a chemical α-pinene that attracts bark beetles and weakens their primary defense of decreasing sap production, which leads to the high mortality of pine trees (Temple et al., 2005).

The relationship between $O_3$ concentration and drought has been documented in the study as well. The high $O_3$ concentration combined with drought stress has been observed to incur less damage compared with high $O_3$ concentration in a more suitable growing environment; this is the result of a lower rate of gas exchange (Temple et al., 2005). Under the same $O_3$ concentration exposure, leaves under favorable conditions, which are typically larger and longer, can sustained more damage than the smaller and shorter leaves under unfavorable conditions (Temple et al., 2005). This finding was also observed in another study conducted in North Carolina where the relationship between $O_3$ concentration and soil moisture was examined. The study suggested that trees growing in wetter sites showed a higher stomatal conductance and a lower photosynthetic rate (Schaub, Skelly, Steiner, Davis, Pennypacker, Zhang, Ferdinand, Savage & Stevenson 2002). It was then observed that a higher rate of gas exchange indicated more severe foliage damage compared with drier sites with low rates of gas exchange (Schaub et al., 2002). Another study has suggested that in alternating periods of wet and drought years, foliage on heavily damaged pines exhibit a higher rate of stomatal conductance in order to offset the loss of growth, but in turn increases the susceptibility to $O_3$ damage (Temple et al., 2005). The results have shown to be consistent with Reich's (1987) study where drought and nutrient deficiency reduce the stomatal conductance and in turn reduces the amount $O_3$ consumed (Schaub et al., 2002).

In general, $O_3$ exposure in California has greatly decreased the coniferous species' needle retention, growth potential, and increased susceptibility to damage in periods of favorable site conditions ("Forest Health Issues", 1996). The different studies have supported the idea that there is a negative relationship between $O_3$ concentrations consumed and photosynthetic activity (Schaub et al., 2002).

## Switzerland

Surveys were conducted on a variety of species in Switzerland in the Canton Ticino regions, and these revealed the typical symptoms of $O_3$ damage. The species sweet cherry (*Prunus avium*), black cherry (*Prunus serotina*), buckthom (*Rhamnus cathartica*), bitter dock (*Rumex obtusifolius*), alpine elder (*Sambucus racemosa*), and wayfaring tree (*Viburnum lantana*) were assessed and analyzed as they were the most sensitive to $O_3$ concentration levels (VanderHeyden, 2001). In contrast to the studies done in California, $O_3$ injuries were not visible on coniferous trees found in South Switzerland.

In open plots with non-filtered chambers, observation was consistent with other studies as symptoms appeared on adaxial stipples, with leaf reddening and premature foliage loss. Symptoms were also observed within an open plot with filtered chambers at 50% ambient, but at a much lower frequency and lower severity of $O_3$ levels (VanderHeyden, 2001). Figures 1 to 3 indicate the responses of different species under open plots and non-filtered plots, with the y-axis as the percentage of foliar damage and x-axis as the AOT40 concentration (Graph from VanderHeyden, 2001).

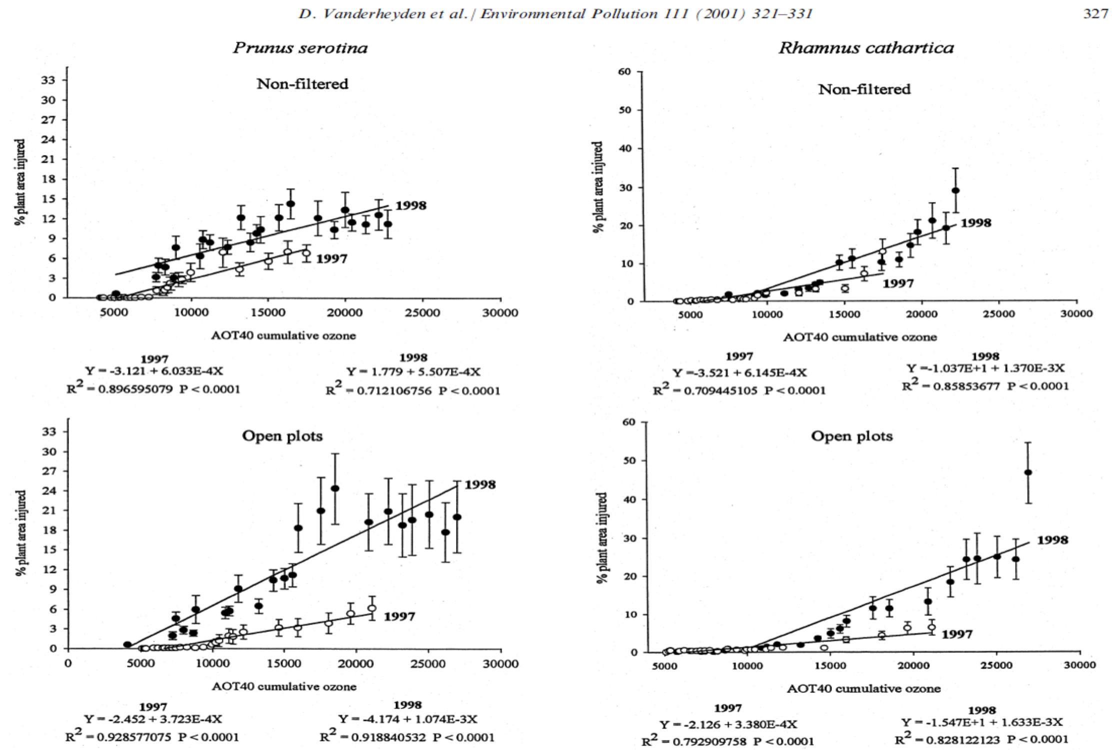


Fig. 7. Regression analysis ($\alpha = 0.05$) of cumulative AOT40 ozone concentration vs. percent plant area injured for *Prunus serotina* in 1997 and 1998 at Lattecaldo Cantonal Forestry Nursery, Morbio Superiore Switzerland.

Fig. 8. Regression analysis ($\alpha = 0.05$) of cumulative AOT40 ozone concentration vs. percent plant area injured for *Rhamnus cathartica* in 1997 and 1998 at Lattecaldo Cantonal Forestry Nursery, Morbio Superiore, Switzerland.

**Figure 1: Effects of $O_3$ concentration on *Prunus serotina* and *Rhamnus cathartica***

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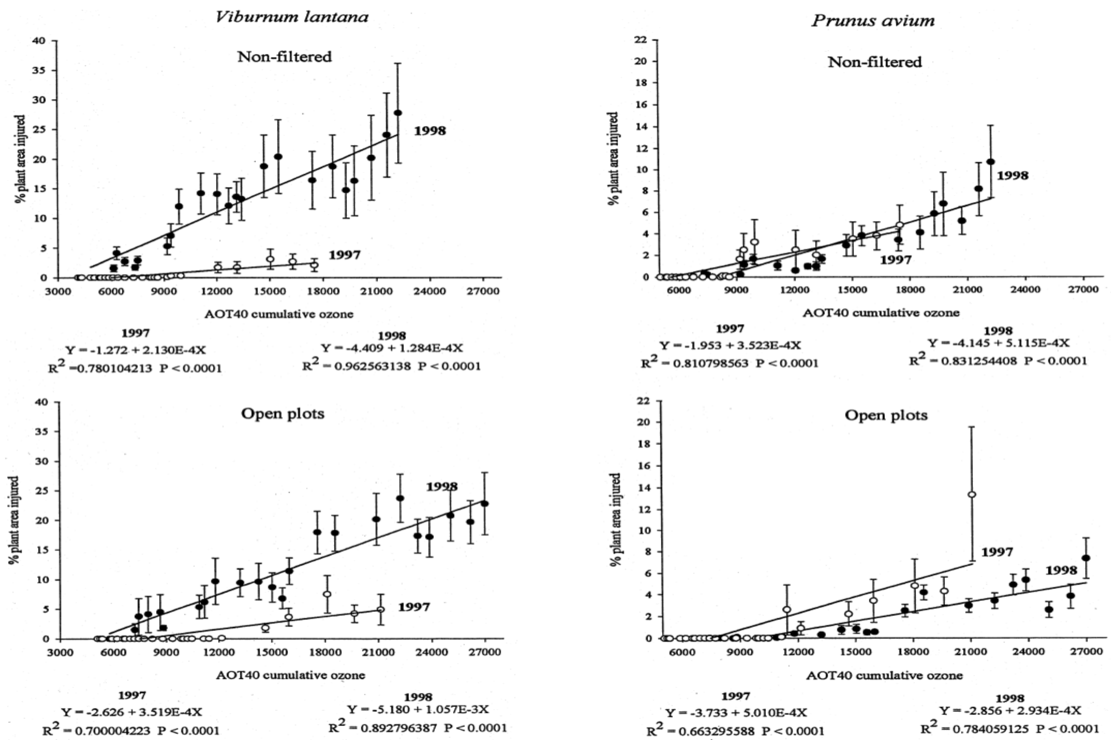


Fig. 9. Regression analysis ($\alpha = 0.05$) of cumulative AOT40 ozone concentration vs. percent plant area injured for *Viburnum lantana* in 1997 and 1998 at Lattecaldo Cantonal Forestry Nursery, Morbio Superiore, Switzerland.

Fig. 10. Regression analysis ($\alpha = 0.05$) of cumulative AOT40 ozone concentration vs. percent plant area injured for *Prunus avium* in 1997 and 1998 at Lattecaldo Cantonal Forestry Nursery, Morbio Superiore, Switzerland.

**Figure 2: Effects of $O_3$ concentration on *Viburnum lantana* and *Prunus avium***

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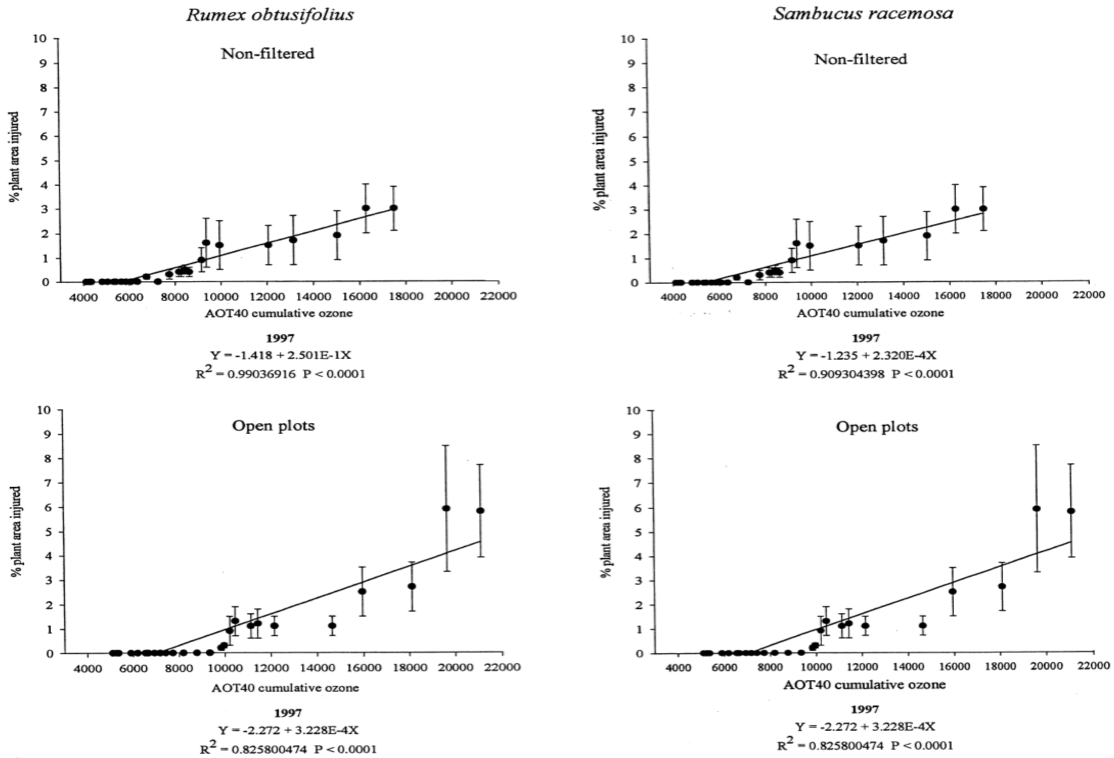


Fig. 11. Regression analysis ($\alpha = 0.05$) of cumulative AOT40 ozone concentration vs. percent plant area injured for *Rumex obtusifolius* in 1997 at Lattecaldo Cantonal Forestry Nursery, Morbio Superiore, Switzerland.

Fig. 12. Regression analysis ($\alpha = 0.05$) of cumulative AOT40 ozone concentration vs. percent plant area injured for *Sambucus racemosa* in 1997 at Lattecaldo Cantonal Forestry Nursery, Morbio Superiore, Switzerland.

**Figure 3: Effects of $O_3$ concentration on *Rumex obtusifolius* and *Sambucus racemosa***

By examining the graphs above, it can be seen that *P. avium*, *P. serotina*, and *R. cathartica* displayed the most sensitivity to $O_3$ concentration levels as they suffered greater damage (VanderHeyden, 2001). In the study, the more sensitive species were observed to have approximately 20-30% of the total leaf area injured due to $O_3$ (VanderHeyden, 2001).

## Problems associated with conducting studies on $O_3$ concentration levels

Historically, studies of $O_3$ have been conducted only on species with economic value and only measured the species' response to growth and yield (Matyssek & Innes, 1999). Accordingly, studies on the effects of growth and reproduction of sensitive species have often been neglected, which can signify a permanent loss of these sensitive genotypes. Although basic evolutionary theory would tend to encourage the survival of fitness to eliminate the weak, the potential loss of these sensitive genotypes leads to a reduction in genetic diversity of the forest as a whole. Genetic diversity is of importance, where one tree might have a greater tolerance towards a certain stressor than another of the same species. By dismissing the importance of sensitive species, we overlook the idea that the whole population may have a lower resistance to different stressors (Matyssek & Innes, 1999).

Indicators used to assess and interpret $O_3$ damage are inconsistent as growth and productivity of the species can fluctuate year to year with numerous variables involved in the process. For example, experiments conducted on broad-leaf trees, shows that the premature loss of foliage can be attributed to a response to high $O_3$ concentration even though no visible injury was observed (Ghosh, Skelly, Innes & Skelly, 1998). Furthermore, the timing of the assessment can play a huge role in determining foliar damage. In the early growing season, shoot growth may exhibit $O_3$-induced damage, but by the end of the growing season, the injured leaves may have abscised. At both times, symptoms may not have developed on young foliage, resulting in problems with accurately measuring $O_3$ damage as there is a reduction in the visible amount of foliar injury (Ghosh et al., 1998; Skelly et al., 1997). Similarly, assessment at the end of the growing season can also suggest that the trees with no visible foliar damage are healthy, but in fact the trees may be suffering high levels of $O_3$ damage, but that all the injured leaves have abscised.

The researchers that assess the impact of $O_3$ concentration play a vital role as many of the studies use foliage injury as the indicator of damage. In a study, if multiple surveyors are used to examine the damage, it raises the concern of bias as each individual can have a different method of evaluating damage. Additionally, most of the study areas have more than two experimental plots, which can imply data collection and assessment across the plots cannot be done within the same period of time. The possibility exists that more injury can occur during the few days assessment is being done on other plots. The experience of the surveyors can also have an effect on the results recorded. It has been noted that environmental stresses can exhibit damage similar to $O_3$ injury (Treshow & Anderson, 1989). For example, the disease “needle blight” found in eastern white pine exhibits “stunting, chlorosis and/or tip necrosis of needles” which can be commonly mistaken for $O_3$

injury (Treshow & Anderson, 1989). In broad-leaved species, symptoms of frost damage and nutrient-deficiency tend to include white flecks, which can be confused with $O_3$ injury (Treshow & Anderson, 1989).

The survey technique involved in assessing $O_3$ injury also raises concerns. As foliage is the indicator of $O_3$ injury, surveyors sometimes used binoculars to look up into the crown. This can result in errors while locating the leaves and the actual damage observed. Furthermore, the assessment of defoliation in the crowns is a poor indicator as there are a lot of ambiguities involved. Depending on the timing of the assessment, the crown can look very different from the beginning to the end of the growing season. Factors such as wind, disturbance, insect and disease outbreaks, and the general health of the tree can affect the appearance of the crown.

The studies reviewed have focused on the effects of $O_3$ concentration on foliage and their correlation with various other factors. Studies have been done independently, focusing on factors such as the effects of increasing or decreasing moisture levels, $O_3$ exposure, nitrogen levels, site characteristics and more. However, there has been little research conducted in conjunction on experimental sites that are similar enough in properties and traits to examine the broader characteristics to gain a complete picture of $O_3$-induced damage. For instance, individuals of the same species can have differing sensitivities to $O_3$ concentration depending on their genetic diversity and geographic location. Within the same species, an individual that has experienced long-term high exposure to $O_3$ at high elevations may have subtle differences from individuals that have only experienced low levels of $O_3$ exposure at low elevations. As a result, it is difficult to understand the exact effects as the development of leaf injury is affected by "nutrition, water availability, temperature, atmospheric humidity, wind speed, and incident light levels", which when combined makes it difficult to identify the potential effects as $O_3$ concentration (VanderHeyden et al., 2001).

## Aggravation of $O_3$ conditions due to wetter conditions

As the opening of stomata and the rate of gas exchange is greatly affected by moisture uptake of the tree species, there is a need to examine the interaction with $O_3$ concentration in depth. Research suggests that when relative humidity increases 35% to 73%, the amount of $O_3$ concentration intake may be enhanced by as much as four times (Treshow & Anderson, 1989). This similarity was found in another study, where foliar injury on *P. serotina* was greatly affected by the correlation between $O_3$ concentration and wet soil conditions--as depicted in Figure 4 (Schaub et al., 2002).

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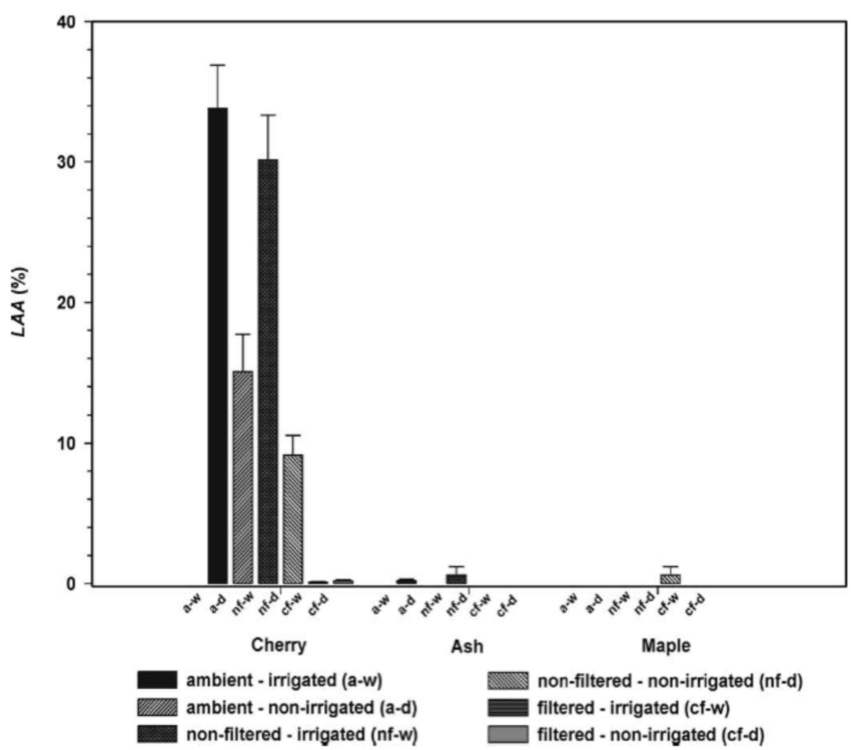


Fig. 4. Average of percentage leaf area (*LAA*) affected by visible foliar injury measured at the end of the season on 17 August 1999. Black cherry, white ash, and red maple seedlings were exposed to ambient (100% $O_3$), non-filtered (98% $O_3$), and charcoal-filtered (50% $O_3$) air on irrigated (w) and non-irrigated (d) soil moisture conditions within open-top chambers and open plots.

**Figure 4: Correlation between $O_3$ concentration and soil conditions on *P. serotina***

The increase in stomatal conductance and decrease in photosynthesis implies a greater consumption of $O_3$, which in turn increases the severity of foliar injury. Interestingly, it has been documented that severely injured *P. ponderosa* under wet soil conditions at low $O_3$ concentration exposure can actually recover from damage, displaying a healthier crown compared to areas with dry soil conditions (Temple, Riechers, & Miller, 1991). However, the recovery can be limited and the future foliage damaged if the area is then subjected to years of drought.

## Future Implications

The effects of $O_3$ concentration can have many different ramifications. In a forest stand, species that are more sensitive to $O_3$ damage exhibit production loss. As long-term exposure to $O_3$ impairs the stomata and leads to leaf abscission, it reduces the tree's rate of photosynthesis, thus the growth rate. The effects of slow growth rates may allow less sensitive tree species to outgrow the more $O_3$-sensitive species. The outcome could create a change in species composition over time, with competition outgrowing the sensitive species.

The effects of greenhouse gases have led to an increase in temperature in some parts of the world. The government of British Columbia has projected that "north eastern areas may become wetter", while the "southern and coast are both projected to become drier in the summer" (Ministry of Environment, 2007). As most studies conducted have focused on the correlation between $O_3$ concentration and drought, there is a need to examine the effects in north eastern B.C where areas may possibly become wetter. As wet soil conditions mean a higher transpiration rate, thus a higher photosynthetic rate, the area might be subjected to a negative relationship with $O_3$. With the stomata opened longer and an increased exposure of $O_3$ concentration, increased foliar injury seems likely. This raises a concern when dealing with commercially high-valued trees in either natural or managed stands. Increased moisture content will have a negative impact on $O_3$-sensitive tree species, but at the same time, water-stressing the trees can limit productivity. As a result, there is a need to study the balance between soil moisture content and $O_3$ concentration to minimize the damage on the forest stands.

## References:

Chaikowsky, C.L.A. 2001. Overview of Ground-level Ozone Observation in Alberta, 1986-1998. *Alberta Environment*. Retrieved from http://environment.gov.ab.ca/info/library/6703.pdf

Edwards, P., Huber, C., & Wood F. (2003). Ozone Exposure and Implications for Vegetation in Rural Areas of the Central Appalachian Mountains, *U.S.A. US Forest Service*. Retrieved from http://www.fs.fed.us/air/documents/$O_3$%20exp%20in%20cen%20App%20Mt.pdf

Forest Health Issues. (1996). 1996 *National Technical Report on Forest Health.* Retrieved from http://fhm.fs.fed.us/pubs/96air.htm

Ghosh, S., Skelly, J.M., Innes, J.L., & Skelly, L. (1998). Temporal development of visual ozone injury on the foliage of *Prunus serotina*—a statistical evaluation. *Environmental Pollution*, 102 (2-3), 287-300. Retrieved from http://www.sciencedirect.com.ezproxy.library.ubc.ca/science/article/pii/S0269749198000578

Krzyzanowski, J., McKendry, I.A., Innes, J.L. (2005). Evidence of elevated ozone concentrations on forested slopes of the Lower Fraser Valley, British Columbia, Canada. *Water, Air, & Soil Pollution*, 173 (1-4), 273-287. DOI: 10.1007/s11270-005-9072-z

Matyssek, R., & Innes, J.L. (1999). Ozone - A risk factor for trees and forests in Europe?. *Water, Air, & Soil Pollution*, 116 (1-2), 199-226. DOI: 10.1023/A:1005267214560

Ministry of Environment. (2007). Climate Change. *Environmental Trends 2007*. Retrieved from http://www.env.gov.bc.ca/soe/et07/04_climate_change/overview.html

Paoletti, E., Bytnerowicz, A., Anderson, C., Augustaitis, A., … Percy, K. (2007). Impacts of Air Pollution and Climate Change on Forest Ecosystems —

Emerging Research Needs. *The Scientific World Journal*. Retrieved from http://aspenface.mtu.edu/pdfs/2007.02.52.pdf

Schaub, M., Skelly, J.M., Steiner, K.C., Davis, D.D., Pennypacker, S.P., Zhang, J., Ferdinand, J.A., Savage, J.E., & Stevenson, R.E. (2002). Physiological and foliar injury responses of *Prunus serotina, Fraxinus americana*, and *Acer rubrum* seedlings to varying soil moisture and ozone. *Environmental Pollution*, 124, 307-320. Retrieved from http://www.sciencedirect.com/science/article/pii/S0269749102004621

Skelly, J.M., Innes, J.L., Savage, J.E., Snyder, K.R., Vanderheyden, D., Zhang, J., & Sanz, M.J. (1999). Observation and Confirmation of Foliar Ozone Symptoms of Native Plant Species of Switzerland and Southern Spain. *Water, Air, & Soil Pollution*, 116 (1-2), 227-234. Retrieved from http://search.proquest.com.ezproxy.library.ubc.ca/docview/17385209?accountid=14656

Skelly, J.M., Innes, J.L., Snyder, K.R., Savage, J.E., Hug, C., Landolt, W., & Bleuler, P. (1997). Investigations of ozone induced injury in forests of southern Switzerland: Field surveys and open-top chamber experiments. *Chemosphere*, 36 (4-5), 995-1000. Retrieved from http://www.sciencedirect.com.ezproxy.library.ubc.ca/science/article/pii/S0045653597101618

Temple, P.J., Bytnerowicz, A., Fenn, M.E., & Poth, M.A. (2005). Air Pollution Impacts in the Mixed Conifer Forests of Southern California. *US Forest Service.* Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr195/psw_gtr195_2_10_Temple.pdf

Temple, P.J., Riechers, G.H., & Miller, P.R. (1991). Foliar injury responses of ponderosa pine seedlings to ozone, wet and dry acidic deposition, and drought. *Environmental and Experimental Botany,* 32 (2), 101-113. Retrieved from http://www.sciencedirect.com/science/article/pii/009884729290035Z

Treshow, M., & Anderson, F.K. (1989). *Plant Stress from Air Pollution*. John Wiley & Sons Ltd.

VanderHeyden, D., Skelly, J., Innes, J., Hug, C., Zhang, J., Landolt, W., & Bleuler, P. (2001). Ozone exposure thresholds and foliar injury on forest plants in Switzerland. *Environmental Pollution*, 111 (2), 321-331. Retrieved from http://www.sciencedirect.com.ezproxy.library.ubc.ca/science/article/pii/S0269749100000609

Zhang, J., Ferdinand, J.A., Vanderheyden, D.J., Skelly, J.M., & Innes, J.L. (2001). Variation of gas exchange within native plant species of Switzerland and relationships with ozone injury: an open-top experiment*. Environmental Pollution*, 113 (2), 117-185. Retrieved from http://www.sciencedirect.com.ezproxy.library.ubc.ca/science/article/pii/S0269749100001755