Ecosystems

Atmospheric Pollutants and Greenhouse Gases

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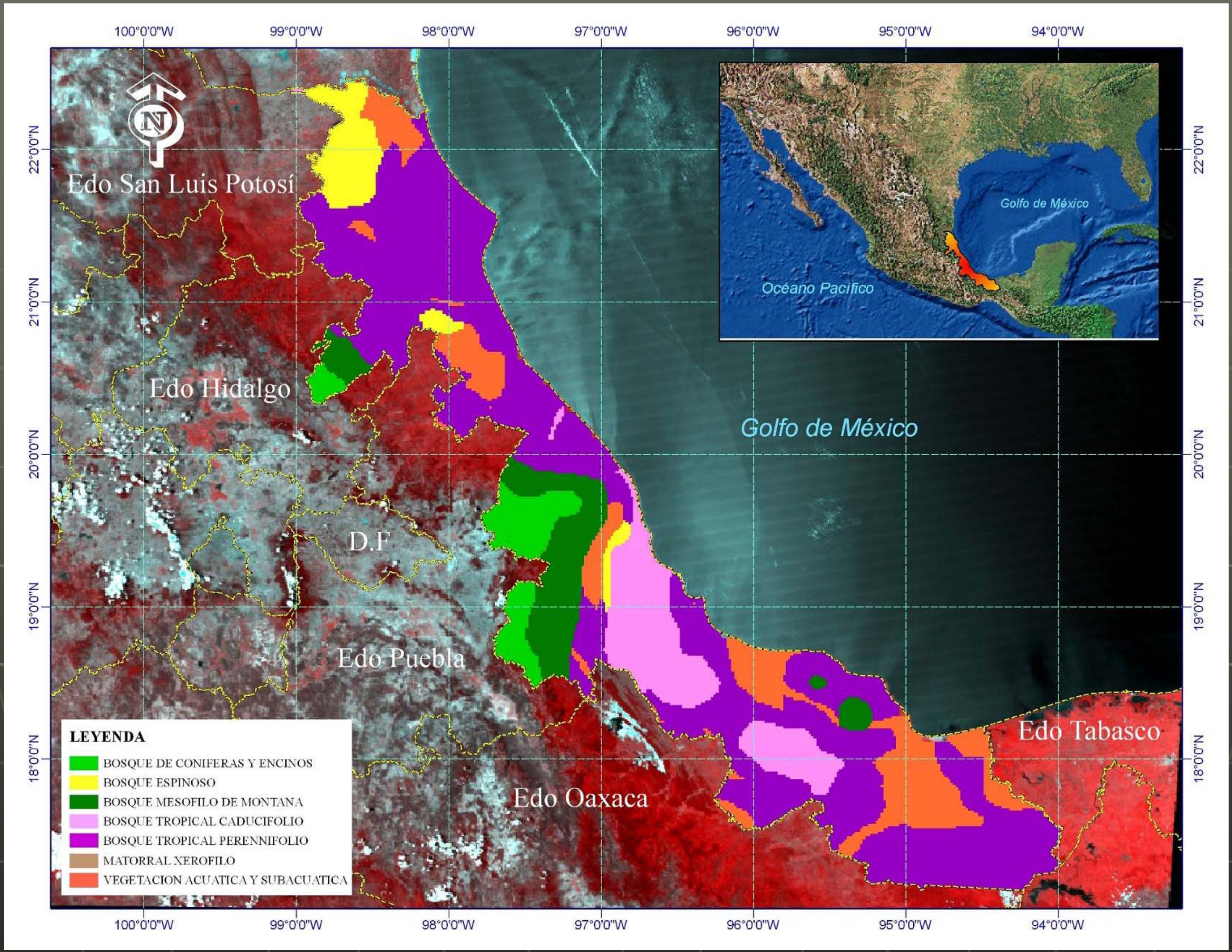
INTRODUCTION

- North America (NA) has been divided into broad ecoregions that contains similar communities of terrestrial and aquatic plants and animals that have adapted to fit the climate and soil of the sites where they are found. The region encompasses a wide range of climate, ecosystems, and population density, and generate a complex mix of gaseous, dissolved and particulate chemical species, acidic and oxidizing compounds, trace metals, and a wide variety of deleterious organic substances (UNEP, 1999).

- Effects of air pollutants on ecosystem health and function date to the first industrial revolution in Europe, but are a more recent phenomenon in NA, dating to the 19th century. Scientific documentation of air pollutant effects on vegetation in NA dating to the 1960s. The study of air pollutant effects on aquatic systems in NA began to appear in the 1970s.



Potential vegetation map

MAJOR AIR POLLUTANT AFFECTING ECOSYSTEMS IN NA

Acid precipitation

- Acid precipitation is a general term that describes the deposition of strong acids from the atmosphere in rain and snow as well in gaseous and particulate form that primarily originates from human activities. Sulfuric and nitric acids are the dominant forms along with small amounts of hydrochloric acid, and originate mainly from the combustion of fossil fuels for energy generation and transport. Pure rainwater has a pH of about 5.66 due to the dissolution of carbon dioxide to form carbonic acid; although the concentration of carbonic acid in precipitation has increased in recent decades due to greenhouse gas emissions. pH values can vary regionally in NA from 4.5 to > 7 (so a pH value < 5.0 can be considered a general indicator of acid rain).
- Although ammonium is not considered an acid in precipitation, this ion contributes to ecosystem acidification through the release of hydrogen ions from conversion to nitrate during microbial nitrification (Stoddard, 1994). Agriculture is the primary, but not the sole source of ammonia emissions.

- Acid rain effects were first recognized as a problem for soils and freshwaters in NA in the 1960s. Ecological research during the 1980s also conclusively demonstrated that ecosystem acidification and degradation was caused by acid rain (Schindler, 1988).
- The mean annual pH of precipitation in Mexico varies widely from 6.48 in the predominantly agricultural Guanajuato State to 4.6 in coastal Veracruz State (Baez et al, 1989). The effects of acidification in heavily polluted parts of Mexico such as the Mexico City valley are different from those known to occur in the wetter, northern parts of the continent, as well as in less polluted portions of the US southwest.
- Currently, acidic atmospheric deposition has been detected in several ecosystems affected by air pollutant dispersion from either populated urban or industrial areas. The vulnerability of important forest types in Mexico (pine forest, 2350-4000 meters above sea level (masl), fir forest, 2700-3600 masl, oak forest, 2350-3100 masl, cloud forest, 2500-2800 masl, juniper forest, 2450-2800 masl, and scrub oak forest, 2350-3000 masl) to acidification is high, and these systems have the potential to become highly disturbed and stressed, as well as susceptible to insect damage.




Acidification from Acid Deposition

- Ecosystem cycling rates of atmospherically-deposited sulfur differ between northern and southern NA. Soils in the north and in high elevation are older and more highly weathered. This difference as well as the warmer climate in the south, generally results in a thinner organic soil horizon in the south, and a greater amount of iron and aluminum hydroxide in the mineral soil, with a large capacity to adsorb atmospherically-deposited sulfate (Rochelle et al., 1987). The longer growing season and higher ecosystem productivity in southern terrestrial ecosystems favor greater rates of nitrogen uptake in vegetation, and therefore a lesser role for nitrate in ecosystem acidification in the south.
- Changes in fish populations are the most widely reported effects of acidification on freshwater ecosystems, losses of other aquatic organisms has also been documented. Comprehensive estimates of the amount of aquatic habitat that has been affected by or depleted of species due to acidification is difficult because of the large and varying number of species that can be present, and the role of mitigating factors or other human activities.

- Fog and cloud water intercepted by the forest canopy can be acidic enough (pH 3.0-3.5) to directly erode plant leaf surfaces (Schemenauer, 1986; Cox et al., 1990), reducing their resistance to pathogenic fungi. Other work from Mexico suggest that the direct action of acidic rain can corrodes leaf surfaces, causes bark peeling and increases the acidity levels of wood (Savedra-Romero et al., 2003; Calva et al 1995).
- Effects of acid deposition on soil calcium have also been demonstrated in Mexico. In Veracruz State, three gas processing facilities emit 5381.9 g s-1 of SO_2 (Bravo et al. 1985), and in the vicinity of these facilities, Mora (2005) measured a daily dry deposition of 100 to 117 µg SO_2 m-2. Siebe et al. (1999) studied the soils along a 12 km transect downwind of the facility, and observed a small decrease in soil pH, but a large loss of exchangeable Ca and Mg, paralleled by an increase in soil sulfate and exchangeable Al concentrations. They mapped the affected area around one facility by measuring the Ca/Al ratio in the upper 20 cm of the soils, and found that 4 ha were severely impacted and another 1500 ha moderately impacted by acid deposition.

Effects of Atmospheric Nitrogen Deposition

- In the 1970s and early 1980s, sulfate was viewed as the major driver of ecosystem acidification because approximately two thirds of the strong acidity in acid rain originated from sulfuric acid and sulfate was the major anion present in most surface waters. This view began to be modified with the recognition that atmospheric nitrogen (N) deposition was in excess of ecosystem assimilation capacity across parts of NA and Europe (Aber et al., 1989).
- Deposition of the major air pollutants, acidity, ozone and nitrogen to forested ecosystems all conspire to increase plant shoot to root biomass ratios, either by inhibiting root development, by changing carbon allocation patterns, or by increasing soil toxicity through increases in aluminum availability in soils. Nitrogen deposition may also stimulate canopy growth by foliar feeding and by-passing the root periodicity controls of excessive nitrogen uptake. The accumulative disproportion of root to shoot biomass ratio are likely causes of rapid declines in affected forest trees promoted by extreme weather events that further injure roots (extended winter thaw) or exacerbated by drought.

- In the northern Chihuahua desert of Central New Mexico, USA, N deposition increased at an annual rate of 0.049 Kg ha-1 yr-1 between 1989 and 2004. Analysis of data suggested that continued atmospheric N inputs were likely to increase grass cover, decrease legume abundance, and could favor blue grama at the expense of the current dominant species black grama (Baez et al 2007).
- Eutrophication and hypoxia are widespread in estuaries throughout NA including Long Island Sound, the Chesapeake Bay, and the Gulf of Mexico near the Mississippi River Delta (Diaz, 2001). Nitrogen is usually limiting to algal productivity in coastal marine estuarine ecosystems, so that nutrient enrichment and hypoxia in estuaries has often been attributed to riverine N.

Ozone and Terrestrial Ecosystems

- Ozone (O_3) is incorporated in acid fog droplets resulting in the production of peroxides which react with sulphite (dissolved SO_2) to produce sulphate and a proton, which increases the acidity of the droplet. This process is believed to occur in the water film on the leaf surface formed during a fog event, magnifying the effects of acid deposition. Over the past 50 years, a large volume of literature has documented the effects of O_3 on forest trees in the U.S. First was the discovery during the 1940's-1960's of the phytotoxicity of O_3 to forest trees. Later, plant population changes related to O_3 were demonstrated in NAn forest trees. This observation was followed by the demonstration that ambient O_3 decreases tree growth and productivity, and that O_3 exposure is linked with shifts and plant communities.
- Ozone effects are known to cascade through tree gene expression, biochemistry, and physiology, ultimately feeding back to productivity, predisposing trees to pest attack and causing changes in water-use efficiency.

- Because carbon enters trees through leaves via photosynthesis, the impacts of pollutant gases on leaf morphology, chlorophyll content, stomatal density and conductance, leaf area in the canopy, and phenology of leaf display play critical roles in carbon budgets of forest trees (Karnosky et al., 2005).
- The effects of O_3 exposure on plants have also been documented in Mexico. Biomarkers of O_3 exposure were investigated at macroscopic and microscopic levels in *Abies religiosa* (Sacred fir) from Desierto de los Leones in central Mexico (Alvarez et al., 1998). One of the most obvious effects of the O_3 on plants was chlorosis and necrosis initially expressed as discrete lesions scattered over the needles. This was followed by premature scenescence and loss of the needle, reduced tree growth and vigor, predisposition to bark beetles and tree death (Alvarez et al., 1998). Recent Mexican investigations have also indicated that indirect effects such as limited root colonization by symbiotic fungi on ozone-damaged *Pinus hartwegii* trees is occurring leading to a reduction of the natural regeneration of this species (Bauer and Hernadez, 2007).

Role of Mercury and Other Metals

- Mercury (Hg) is readily transported long distances in the atmosphere and is deposited to ecosystems in precipitation, gaseous, or particulate bound form: is an environmental concern because it acts as a powerful neurotoxin; its effects can be fatal to humans and animals beyond certain threshold levels. Several catastrophes have demonstrated the toxicity and widespread human health effects of mercury poisoning at high levels. In metallic or gaseous elemental form, Hg is relatively harmless in ecosystems, but when methylated by bacteria, it becomes bioavailable and can be readily biomagnified through food webs (Rudd, 1995; Mergler et al., 2007).
- There are many examples of localized Hg contamination of ecosystems such as in mining areas, burial or discharge of industrial waste. The large sources of Hg emissions have been reduced in NA with management and remediation improvements. The problem however, has now shifted to atmospheric deposition of low levels of Hg from remote sources, including coal-fired power plants, medical waste incinerators, other industrial emissions, and also include natural emissions from sources such as volcanoes and soils.

- Field-based studies suggest that dry deposition of Hg may be underestimated by many models. Recently emerging evidence suggests that litterfall-derived estimates of dry Hg deposition may be enhanced by emissions of previously deposited Hg from surrounding soils.
- Mercury contamination of ecosystems is widespread in NA. In the U.S. for example, Hg was responsible for 80% of all state fish consumption advisories in 2006, and 48 States plus 1 Territory had advisories attributed to Hg. In addition to the human health effects of consuming fish contaminated with methyl Hg, bioaccumulation has demonstrated effects on piscivorous birds which consume fish with elevated Hg levels and fish eating mammals. Certain fish species show effects which include toxicity, reproductive impairment, and non-toxic neurological impairment (Scheuhammer et al., 2007).
- The largest Hg pool globally is contained in soils, whereas in forested ecosystems, the vegetation pool is often second largest (Grigal, 2002, Mason and Sheu 2002). The soil pool is typically concentrated in the top soil layers, and is strongly associated with organic matter as discussed above.

- Atmospheric deposition of other metals, such as nickel, copper and cadmium can also have severe ecological impacts in aquatic systems (Hutchinson & Havas, 1986). Metals can cause toxicological effects on invertebrates, as well as on fish. Metals are most toxic in acidic waters, because low pH favors the dissolved ionic form which is more easily taken up by biota (Nelson & Campbell, 1991). Another metal not transported atmospherically, but made available in a toxic form under acidic conditions is aluminum which is the most common metallic element in rocks. Under low pH conditions, ionic Al binds to fish gills, eventually causing suffocation (Baker & Schofield, 1982).
- The atmospheric deposition of metals can also have ecological impacts in terrestrial ecosystems (Hutchinson & Whitby, 1977). High concentrations of heavy metals such as zinc (Zn), copper (Cu), manganese (Mn), nickel (Ni), cobalt (Co), cadmium (Cd), lead (Pb) and Hg in soils have an adverse effects on microorganisms and microbial processes, especially with those of mycorrhizal fungi which provide the link between soils and roots (Leyval et al., 1997), leading to problems such as reduced plant growth or mortality.

- In the U.S. and Canada, Pb was eliminated from gasoline through federal legislation in the early 1980s, but only in 1990 in Mexico. Lead levels are found to be two to four times higher in forests to the south of Mexico City than to the north, indicating north to south atmospheric transport (Zambrano et al. 2002). Additionally, Pb as well as many other trace metals have been detected in tree rings of *Pinus* and *Abies* from forests surrounding the Mexico City Valley. Some of these metals such as Fe and Zn may be correlated with vehicle emissions, but also may be influenced by recent volcanic activity in the region. Other metals such as Mn may be affected by local soil acidity such as in the Desierto de los Leones (Calva et al 2006). Lichen species in the Mexico Valley have also shown enhanced accumulation of many metals that are transported through the atmosphere from pollutant sources. The deposition patterns of vanadium (Va), arsenic (As), selenium (Se), Cd and Pb are substantially influenced by long-range transport from Mexico City, whereas Cr, Fe, Co, Ni, and Cu show deposition patterns that are largely determined by contributions from point sources within Mexico (Aspiazu et al 2007).

- Metal contamination due to atmospheric deposition may have also affected aquatic ecosystems in Mexico, and metal-associated transport can be enhanced by local land use practices. For example, sediment at Lago Verde, a freshwater marsh on the lower slopes of San Martin volcano in Los Tuxtlas, Mexico, and currently the northernmost remnant of the tropical rain forest, shows evidence of accelerated erosion rates related to the clearing of large forested areas at Los Tuxtlas and higher accumulation rates of heavier and more magnetic sediments.
- Recent sediments from Lago Verde were enriched in Pb and moderately enriched in Cd, Cu, Zn and Hg. This lake occupies a relatively pristine, non-industralized basin and therefore, increased metal fluxes are likely related to long distance aeolian transport of trace metals (Ruiz-Fernandez et al 2007).

Persistent organic pollutants (POP's)

- Refers to a series of polychlorinated biphenyl compounds. Many, such as polychlorinated bi-phenyl (PCB’s), have been synthesised for industrial purposes, others such DDT, Lindane, chlordane were produced for agricultural or pest control uses, while others occur as a result of accidental by-products of combustion or the industrial synthesis of other chemicals.
- There are a number of reasons why POPs are an environmental concern: they degrade slowly, are highly volatile and are lipophilic. Moreover, most of these compounds are bioaccumulative and toxic. They typically biomagnify in aquatic and terrestrial food webs and have long atmospheric residence times. Thus top predators and human consumers of traditional diets that are high on the food chain are exposed to elevated concentrations in their food supply. For example, Inuit mothers in Northern Quebec had 5-fold higher concentrations of PCBs in their milk than southern Canadians.

- Atmospheric transport and incorporation into forested vegetation has been documented in Mexico. In a study that compared concentrations and source characterization of polycyclic aromatic hydrocarbons (PAHs) in pine needles from Korea, Mexico, and the U.S., total PAHs concentrations ranged from 31 to 563 ng g^{-1}, the highest concentrations were found in samples collected in forests close to Mexico City. The ratios of methylphenanthrene to phenantherene suggest that the contribution of diesel-operated vehicles to the signature of PAHs is more significant in Mexico than in Korea and the U.S. (Hwang et al., 2003).

ECOSYSTEM ACCOUNTABILITY FOR AIR POLLUTION CONTROLS

- Accountability for assessing air pollution effects on ecosystems is usually accomplished with a combination of data from field studies that use monitoring or research approaches, and predictive modeling. Monitoring programs are designed to assess spatial and/or temporal changes in sensitive or representative ecosystems. Temporal monitoring networks usually need to be long-term in duration, while spatial monitoring studies provide an indication of the extent of a problem. Very often, monitoring programs are unable to sustain the funding or institutional support required to maintain a data record long enough to show relevant changes and their causes (Lovett et al., 2007). A number of successful long-term programs do exist that allow an assessment of air-pollutant relevant ecosystem changes, and these are described below.

- There are different approaches to measuring air pollutant effects in ecosystems. Monitoring networks can be specifically designed to evaluate water chemistry or ecosystem components such as fish or bird populations. These are usually set-up by government agencies responsible for environmental protection, or industries which are mandated to monitor air pollutant effects on ecosystems.
- Another level of assessment is through research studies. These can be carried out in laboratories or in the field (or a combination of both) and are used to understand and quantify geochemical and biological processes which occur in environmentally stressed systems. Many research sites are also currently being maintained in NA, focussing on various ecosystem pollution issues. As of yet, there are no similar sites in Mexico where intensive research is being carried out.

Monitoring the Effects of Atmospheric Stressors

Acid Deposition Effects Monitoring

- Despite the critical role that soil chemistry plays in the acidification of ground water and surface water, little effort has focused on surveys of soil chemistry in acid deposition assessment efforts.
- By the late 1990s, alkalinity and pH had generally not increased as expected in many of the monitored NAn water bodies because base cation (calcium, magnesium, potassium, sodium) were decreasing as rapidly, or more rapidly than the strong acid anions reduction, probably due to long-term base depletion in soils from decades of acid deposition (Stoddard et al., 1999).
- Biological recovery is also likely to vary depending on trophic level, with the most rapid recovery expected at the lowest trophic levels. Studies also show that factors such as dispersal and competition with acid-tolerant species will complicate recovery trajectories

- The acidification effects on Mexican ecosystems are mostly experienced by plants because there are few major freshwaters in this country and these are usually located on bedrock insensitive to acidification. A number of studies have looked at the effects of acidification on plants, but though these studies have identified existing problems of plant health, there are no recurring monitoring programs that evaluate plant health in relation to acid deposition,
- There are also studies in Mexico that demonstrate deleterious effects of air pollutants on agricultural crops. For example, studies have found that the susceptibility to fungal opportunistic pathogens increased in mango plantations located downwind from a thermoelectric power plant and was associated with acid rain and Ni- and V-rich ash exposure that affected the fruit peel. (CFE Report, 2003; Siebe et al. 2003). The plant burned sulfur-rich fossil fuels and emitted particles of graphite-like C with precipitates of VSO_4- and $NiSO_4$. Close to the source (2-4 km distance) up to 18.5 g m^{-2} particles were deposited along with 148 mg V and 39 mg Ni. These metals enter the environment in a mobile form, and are readily taken up by the mango tree leaves. Nevertheless, translocation into the fruits was very small.

- Systematic study of the chemical composition of precipitation in Guanajuato State, one of Mexico's most important agricultural areas, allowed the determination of the precipitation contribution of N to soils. The total amount of inorganic N deposited to soils ranged from 6 to 17 Kg ha^{-1}, representing 5.7 to 22.8 % of the N applied as urea fertilizer during the growing season (Baez et al 1989). Direct foliar N uptake is known to be an important process in some Mexican forest ecosystems.
- Under greenhouse conditions, a high potential for foliar uptake of N as nitrate and ammonium was demonstrated for Abies religiosa. Additionally, coniferous forests of the Valley of Mexico receive N deposition 4 to 11 times greater than under natural conditions, indicating the importance of investigating the effects of this excess N deposition on these forests (Chavez Aguilar et al., 2006).

Ground Level Ozone: Monitoring and Impacts

- Over mid-latitudes, background O_3 levels have risen by approximately 100% since the beginning of the 20th century, though increases in atmospheric concentrations have levelled or decreased since the 1990s.
- Spatial assessments across NA have shown that O_3 is the most pervasive air pollutant in NA that cause direct damage to vegetation in natural areas (Percy and Karnosky, 2007). Surface-level O_3 threatens forests in both the northern and southern hemispheres (Percy et al., 2002), as well as near urban areas such as Mexico City. Many natural areas have been experiencing decreased visibility, increased O_3 levels and elevated nitrogen deposition. High O_3 concentrations have been a major documented pollution problem in the Mexico City basin for at least 10 years, exceeding the Mexican standard of 110 ppbv.

- The first report on oxidant-induced damage in the Valley of Mexico was presented more than 30 years ago. There is now considerable evidence of ozone pollution in the Desierto de los Leones National Park, 25 km southwest of Mexico City, (Bauer and Krupa 1990, Alvarado et al. 1993, Skelly et all 1997), and data from an O_3 monitor during 1990 and 1991 displayed frequent violations of the Mexican air quality standard (Bravo and Torres 2002, Miller et al 2002, RAMA http://www.sma.df.gob.mx/simat/consultas.htm).
- A 30% decrease in maximum net photosynthesis and 18% chlorophyll b degradation were detected in a forest near Mexico City (Zambrano and Nash 2000). Also in the same region, the epiphyte lichen community was shown to have 47% fewer species, 62% less lichen cover, and a species abundance pattern that revealed a highly disturbed community, compared to control sites. Air quality, mainly high ozone levels, may account for many of the observed differences. (Zambrano et al 2000).

Persistent Organic Pollutants monitoring

Persistent Organic Pollutants: Monitoring Results

- The two most studied regions in NA regarding persistent organic pollutants are in the Great Lakes region due to the important of these lakes for drinking water and fishing supply for a large population, and the Arctic, where contaminant concentrations are magnified due to atmospheric transport into simple, slow growing food webs. Moreover, aboriginal people are highly dependent on large fish and mammals for their food supplies which leads to dangerously high concentrations in humans.
- A large number of studies on POP concentrations in nature and in human populations are ongoing and that due to the persistent nature of these compounds, that interest in them will continue for a long period.

Predicting Ecosystem Changes with Pollution Management

Predicting Future Ozone Effects

- The interaction of O_3 with trees is a complex process that varies in response to a host of environmental, ecological, and other factors (Kubiske et al., 2006; Percy et al., 2002) and this complexity presents great challenges for scaling impacts beyond the tree level (Samuelson and Kelly, 2001). Many models used previously to predict forest productivity change due to O_3 effects (Ollinger et al., 2002; Felzer et al., 2004) have assumed a degree of linearity in response to O_3 exposure. Yet, we know that plant response to O_3 is intrinsically non-linear. Increasing CO_2 and O_3 levels can lead to both stomatal closure, which reduces the uptake of either gas, and in turn limits the damaging effect of O_3 and the CO_2 fertilization of photosynthesis.

- Recently, Sitch et al. (2007) have estimated the impact of projected changes in O_3 on the land-carbon sink, using a global land carbon cycle model modified to include the effect of O_3 deposition on photosynthesis and to account for interactions between O_3 and CO_2 through stomatal closure. For a range of sensitivity parameters based on manipulative field experiments, they found a significant suppression of the global land-carbon sink as increases in O_3 affected plant productivity. As a consequence, CO_2 accumulation in the atmosphere was enhanced. They suggest that the resulting indirect radiative forcing by O_3 effects on plants could contribute to global warming to a greater extent than the direct radiative forcing due to tropospheric O_3 increases.
- Using five-years of co-measured O_3, meteorology and growth response, Percy et al (2007a) have developed exposure-based regression models that predict Populus tremuloides (trembling aspen) growth change within the NAn ambient air quality management context.

MULTIPOLLUTANT EFFECTS ON ECOSYSTEMS

- Atmospheric stressors rarely operate individually. Ecosystems are usually simultaneously affected by two or more atmospheric pollutants or other stressors, whose effects can combine to either amplify or alleviate the effects on receptor ecosystems.
- In late 1980s, researchers studying acid deposition effects were focusing on the combined effects of sulphur and nitrogen deposition. Recent research has increased our understanding of multi-pollutant interactions such as those of nitrogen and sulphur with calcium, as well as mercury with sulfur acidification. Additionally, given recent climate change research and the high likelihood of larger variations in temperature and precipitation in coming decades, it is imperative to understand how climate and the carbon cycle interact with nitrogen. sulfur, ozone, and mercury. Greater understanding of these multi-pollutant interactions will better provide: (1) science-based adaptive strategies to maintain ecosystem health and productivity for land owners and managers, and (2) justification and accountability for control of multiple emissions sources.

Nitrogen, sulfur, and mercury pollutant interactions in ecosystems

- Acid rain is fundamentally a multi-pollutant problem with sulphuric and nitric acids both contributing to ecosystem acidification. Although early acidification research focused more strongly on sulphuric acid, the importance of nitric acid has generally been well recognized since the 1980s, and most investigations of acid deposition and acidification since that time have studied both sulphuric and nitric acid effects.
- In the majority of NAn fresh waters, phosphorus is the nutrient that limits aquatic productivity. Increases in phosphorus would then be expected to most widely affect mercury biodilution. However, in many waters, nitrogen is a limiting or co-limiting nutrient (Elser et al., 1990), so nitrogen is also expected to affect mercury biodilution in some systems.

Climate Change and the Carbon Cycle

- NA has warmed by about 0.6^{o} C during the 20th century, and this warming has accelerated since the 1970s. The consensus is that climate warming is caused by increases in greenhouse gas concentrations that largely result from human activities such as the burning of fossil fuels and deforestation (IPCC, 2007). The warming measured to date is believed to be driven mainly by CO_2 concentrations that have increased from about 280 ppm in 1750 to 381 ppm in 2006 (Canadell et al., 2007), and are at their highest levels in the past 650,000 years (Siegenthaler et al., 2005). Increasing concentrations of other greenhouse gases such as methane and chlorofluorocarbons have also been measured in recent decades, and together these gases are believed to account for about 37% of current radiative forcing (Forster et al., 2007).
- Projected energy consumption and economic growth combined with global climate models indicate that increases in greenhouse gas concentrations accompanied by additional warming are likely to continue for the foreseeable future. However, increased awareness of the consequences of global warming may impel actions to reduce greenhouse gas emissions and slow the current warming trend in coming decades.

Interactions of the Carbon Cycle with S and N pollutants

- A large number of studies have explored how climate change may affect linkages between the nitrogen and carbon cycles. There is evidence to support that warmer temperatures increase the rate of nitrification and nitrate leaching in humid ecosystems of the Northeast that receive high loads of atmospheric nitrogen deposition (Murdoch et al., 1998), but the likely long-term persistence of these patterns with future climate change and increases in atmospheric CO_2 concentrations is unknown.
- An important concern regarding nitrogen air pollutant effects and climate change is how increases in atmospheric CO_2 concentrations will interact with nitrogen limitation of forested ecosystems in NA. Despite the acknowledged role of air pollutant NOx in elevated rates of atmospheric nitrogen deposition over much of NA, most temperate and boreal forested ecosystems in NA show evidence of responding to increasing nitrogen deposition through increased net ecosystem productivity and carbon sequestration (Magnani et al., 2007).

Interactions of the Carbon Cycle with Mercury

- Mercury has a complex cycle in the environment that includes natural and human emissions sources, wet and dry deposition, biological and abiological storage and cycling processes, and bioaccumulation. Many of these transfer and storage processes may be altered by changes in air temperature and precipitation. For example, methylation is the key process that facilitates uptake, bioaccumulation, and toxicity of mercury in aquatic ecosystems, and like most microbiological processes, methylation rates tend to increase with increasing temperature. However, many other factors such as pH, sulphate availability, redox status, and carbon availability also affect methylation, making it difficult to predict methyl mercury changes by extrapolations based solely on likely temperature responses.
- The emissions that originate from soils, fresh waters, and the oceans may increase as air temperatures increase, though the overall effect of climate change is to introduce greater uncertainty in models of mercury transport and deposition (Lindberg et al., 2007).

Ozone Effects on Forests with Climate Change

- It is widely perceived that future climate change will lead to increased growth and range distribution of some forests. This warming is largely being driven by increased radiative forcing caused by rising levels of greenhouse gases. The third most important greenhouse gas contributing to global average radiative forcing is tropospheric O_3 (Ramaswamy et al., 2001). In the lower troposphere, surface level O_3 has become one of the most pervasive air pollutants at the terrestrial biosphere–troposphere interface (Fowler et al., 1999).
- Karnosky et al. (2003) demonstrated that elevated O_3 at relatively low concentrations can significantly reduce the growth enhancement of elevated CO_2. These results followed similar trends to those of many agricultural crops, other hardwood trees and a few conifers. Taken together, these studies on plants of different genetic backgrounds, growth characteristics, and life histories suggest that O_3 can seriously alter the capacity of vegetation to grow under elevated CO_2 and to sequester carbon. Karnosky et al (2003) further stated that an understanding of O_3 as a moderator of CO_2 responses is essential to improve global models of terrestrial net primary production which currently predict that O_3 levels in the U.S. can largely offset increased forest productivity caused by increasing atmospheric CO_2 concentrations.

CONCLUSIONS

- The ecosystem effects and focus of studies are somewhat different in the arid and semi-arid climate that dominates much of Mexico and the western US and Canada compared with work in eastern NA. For example, in the western US researchers have shown impacts of nitrogen deposition on alpine vegetation, aquatic diatoms, and semi-arid shrubs, whereas work in eastern NA has focused more strongly on the effects of acidification on aquatic biological organisms such as fish and invertebrates.
- The broad picture across NA from the 1980s to today is that sulphur, nitrogen, and mercury deposition as well as ozone levels, are decreasing. However, there are many important exceptions to this generalization that include nitrogen deposition across much of western NA, and ammonium deposition throughout NA which are either stable or increasing. Additionally, evidence indicates that intercontinental transport and deposition of mercury is increasing, especially from Asia to NA, a pattern that is likely to continue. Trends are more difficult to evaluate in Mexico because of the relatively recent development of monitoring networks for atmospheric deposition. Moreover, deforestation is a very important factor in Mexico, further complicating a clear understanding of air pollution effects.

- These trends, however, which are consistent with the beginnings of ecosystem recovery from acidification, are not as great as the declines in precipitation acidity, reflecting lags in these systems. Long-term base cation depletion has been invoked as a likely reason for poor correlations between decreases in the acidity of atmospheric deposition and key aquatic ecosystem indicators such as pH and aluminum concentrations.
- Unfortunately, monitoring in the US and Canada has mainly focused on surface-water chemistry, and few long-term data sets exist to evaluate current trends in soil indicators such as soil base saturation. We note also that the lack of long-term repeated monitoring of soil chemistry is a limitation to the accuracy of models that predict future surface-water chemistry because these models must now rely on few data points and must make unconstrained assumptions of the changes in soil chemistry over time. There has also been little long-term and consistent monitoring of aquatic and terrestrial biota to evaluate recovery trends in sensitive ecosystems. The few studies available indicate little biological recovery to date and suggest that recovery may lag decades behind the recovery of biologically-relevant water chemical parameters.

- An interesting result of the assessment is that little interest was demonstrated by the agricultural research communities in Canada and the US in studying the effects of air pollution on managed ecosystems, unlike the interest that exists in Mexico. As seen above, a number of Mexican studies have linked air pollution to crop damage, especially near urban and industrial sources. From discussions with agricultural experts in the US and Canada, however, air pollution seems to be treated as a problem which can be addressed with modified plant varieties (e.g. developing better leaf resistance to O_3 effects) or by changes in soil management, such as increased liming in areas receiving high acid rain levels.