Impacts of Air Pollution on Forest Ecosystems

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Introduction

Air pollution problems are international in scale. All forests worldwide experience some degree of air pollution exposure above preindustrial levels. Atmospheric transport processes do not recognize geographic borders, but sources of pollutants, the pollutants of concern, and the specific effects of pollutants vary greatly depending on human cultural activities and natural climate patterns. For example, heavy-metal contamination is a result of poorly controlled mining and industrial emissions; when coupled with frequent rainfall, dispersion is minimized and local deposition is maximized. Deposition of suspended particles is most frequently a problem in forests in dry climates adjacent to agricultural areas where atmospheric conditions allow suspended particles to remain airborne for long periods of time. Ozone is a secondary pollutant formed from automobile exhaust (nitrogen oxides) and volatile organic carbon from a variety of chemical, combustion, and natural processes. The reaction requires ample sunlight, thus ozone is a serious problem in urbanized areas in sunny climates.

Air pollution effects on forests can, therefore, best be understood by looking at climate zone and the human cultural activities of agriculture, urbanization, and industrialization. Although there are many natural sources of air pollutants, such as vegetation fires, windstorms, and volcanic eruptions, for the purposes of this article we shall focus on human-caused, or anthropogenic, sources of air pollutants and their effects on forest ecosystems. The effects of elevated carbon dioxide, global climate change, and other abiotic stressors are covered elsewhere in this *Encyclopedia* (*see* **Environment**: Impacts of Elevated CO_2 and Climate Change).

There is still much to be learned regarding air pollution and forest health. For example, nitrogen deposition from agricultural and urban sources is recognized both in Europe and the American continents as having a large potential for changing existing ecological processes and species composition. However, understanding the mechanisms driving changes and the extent of the threat to existing ecosystems is subject to ongoing debate.

Air pollutants can have acute effects arising from very high pollutant loads such as the destruction of forests due to unregulated heavy industrial activities such as in the 'black triangle' of Czechoslovakia, East Germany, and Poland. Alternatively, pollutants can have chronic effects from long-term exposures at lower concentrations such as ozone damage found in southern Californian forests adjacent to the Los Angeles basin. Many of the chronic effects are difficult to identify and catalog. Plant species vary widely in their sensitivity to pollutants and the display of recognizable symptoms. The yellow pines of North America have been a key indicator species for identification of ozone toxicity because of a display of 'chlorotic mottle' (a stippling of the needles) and premature loss of annual whorls. However, the converse is not necessarily true; the lack of a specific suite of symptoms does not necessarily indicate a lack of pollutant effects. Many nonvascular mosses and symbiotic lichens simply disappear from the forests under polluted conditions.

Finally, many air pollutant effects are synergistic with other biotic or abiotic stressors. Heavy metal contamination may weaken a tree, but an insect or pathogen infestation may be the actual cause of death. Drought is part of the natural climatic cycle in semiarid forests, but forests that have experienced extended years of ozone toxicity may be more susceptible to drought-induced mortality.

In the sections that follow, air -pollution effects are described by major climatic zone (**Table 1**). A brief description of the primary environmental factors and human activities that affect pollution loads and distribution within each of the major climate zones is included. It is recognized that for the purposes of this article generalizations are made and many exceptions exist. The reader is referred to other sections in this series and the list of recommended reading for more detailed information.

Subarctic Boreal Forests

Air Pollution Causes

Subarctic forests occur across Asia, North America, and northern Europe; about 70% of the world's boreal forests are in Russia. The subarctic zones

Table 1 Pollutants described within the individual sections

Forest type by climate zone	*Pollutants of concern*
Subarctic	Heavy metals, sulfur dioxide
Wet tropic	Smoke
Semiarid	Ozone, dry deposition, particulates
Temperate	Acid rain

contain rich mineral deposits and extensive timber and coal resources for industrial processing and energy production. Resource extraction is the primary activity in these forests, creating intensely focused, localized sources of industrial pollutants. Little agricultural or urban activity occurs here. Coal mining and logging provide energy resources for local uses and export. Timber resources are also used for paper and wood products, creating air pollutants in the industrial processing of wood fiber. Most of the pollutants in boreal forests are generated from smoke stacks. However, since the human populations are low outside the immediate industrial site, regulations and restrictions based on human health concerns have, historically, been limited and concern regarding forest sustainability has only recently occurred. The climate plays a critical role in air pollution effects on boreal forests. The growing season is, at most, 3 months, with long hours of sunlight available during the summer for gas exchange and photosynthetic activity. During the winter not only does cold inhibit metabolic activity but also daylight hours are short. Boreal forests are slow-growing and slow to recover after disturbances.

Air Pollution Concerns

The effects of air pollutants on boreal forests are acute. The industries of the subarctic generate two primary pollutants of concern: sulfur dioxide and the generalized category of 'metals.' These two pollutants have very different dispersal patterns and modes of action (that is, how they affect trees and forest ecosystems).

Sulfur dioxide is a well-known byproduct of coal combustion, but it is also found in many minerals and is released during smelting. Once aloft, sulfur dioxide can be transported for hundreds of kilometers before depositing on foliage, soil, water, or other substrates. Deposition can occur in rainfall, snowfall, or fog. It is also absorbed by plants as a vapor, and can collect on surfaces in a dry form. Furthermore, sulfur dioxide reacts with a number of other atmospheric compounds to form sulfuric acid, ammonium sulfate, and other vapors or aerosols. Because of its wide dispersal patterns, sulfur dioxide emissions can result in damage to forests over a large geographical area.

Metals, on the other hand, are generally deposited within 10–15 km of the source. Although there are many potential metal contaminants, such as cadmium, uranium, or lead, most of the concerns regarding boreal ecosystems are focused on copper, nickel, and zinc. The tendency for metals to collect relatively close to the source limits their geographic impact, but increases the concentrations and thus the intensity of the effects.

Air Pollution Effect

Mining and forestry operations in Russia have resulted in about 1 million hectares of 'seriously damaged' forest and another 7 million hectares of 'affected' forests. The Noril'sk mining complex is one of the best examples of the catastrophic effects of unregulated mining and smelting on boreal forests. Tree mortality due to sulfur dioxide extends for 200 km downwind of the complex and copper, cobalt, and nickel concentrations in soils are 10–1000 times higher than background levels up to 30 km downwind.

In addition to differences in distribution, the effects of these two primary pollutants differ in several important ways. Sulfur dioxide is phytotoxic as an airborne pollutant while metals are generally most toxic when incorporated into soil systems. Acute exposure to sulfur dioxide results in necrosis (cellular death) of leaf tissue. Often the effects are first displayed as chlorotic spots and later as bleached-white or brown necrotic spots on leaves and needles or along the margins of leaves. As acute exposures progress, the entire foliar surface turns brown and the leaf or needle is abscised from the tree. Acute sulfur dioxide symptoms may begin to occur at ambient concentrations of 50 parts per billion (ppb). Emission episodes resulting in concentrations of 1 part per million (1000 ppb) have been measured around unregulated smelting plants and coal-burning facilities. Chronic exposures to lower concentrations of atmospheric sulfur dioxide cause interveinal chlorosis of leaves and tip burn on needles. Continued exposure at lower concentrations can result in premature shedding of foliage and reduced net primary productivity. Deposition of sulfur dioxide on foliage can cause erosion of the surface cuticle boundary, but more often the uptake through stomata is the primary mechanism for damage. Once in the foliage interior, sulfur dioxide is converted to HSO_3 – bisulfite – a free radical, $SO4_2^-$, or SO_3^-, all of which disrupt metabolic activity or alter plant nutrient balances. In the subarctic boreal forests, the long summer days provide extended periods of gas exchange and this extended period of foliar uptake can result in greater injury symptoms compared to regions closer to the equator. Conversely, during the winter, when days are much shorter and the cold temperatures limit water availability, stomata may not open at all for extended periods. During these times atmospheric sulfur dioxide interactions with the canopy of trees become less important, but deposition to, and accumulation in, soils can have adverse effects, which will be addressed in later paragraphs.

Metals generally do not attack foliage directly. Their effects are most pronounced on roots. Although lumping metals into a single category is scientifically inaccurate, as each element exhibits independent effects ranging from biochemical competition with nutrient ions (for example, zinc and phosphate) to direct inhibition of root tip growth (aluminum), for the purposes of this discussion they will be considered together. Most metals are not easily translocated to the shoots of plants but can have profound effects on root function and the healthy functioning of many soil organisms upon which plants rely for nutrient cycling. Studies of metal-contaminated soils have shown that the microbial communities are frequently altered. In addition, some metal-contaminated soils have reduced rates of litter decomposition, thus lowering nutrient availability. In particular, nitrogen and phosphorus can become growth-limiting. When metal concentrations reach a level such that they seriously inhibit root functions, the trees are no longer able to acquire enough water or nutrients, resulting in stunting of growth and ultimately death. Unlike sulfur dioxide, which may be metabolized and at least temporarily removed from the environment, the lack of uptake, assimilation, or translocation means that metals remain in the environment. Therefore, even relatively low levels of ambient air concentrations can result in metal accumulation in soils. Once a critical load has been achieved, tree mortality occurs.

The presence of both sulfur dioxide and metals is often synergistic, meaning that the effects together are more destructive than the individual effects. The second effect of sulfur dioxide emissions is 'acid rain,' although deposition occurs in any precipitation form. Acid rain has been greatly publicized and is probably the best recognized effect of air pollution. The significance of acid rain effects depends upon many other environmental factors, particularly those related to soil physical and chemical structure. Therefore a universal statement regarding acid rain effects in boreal forest is inappropriate. However, one of the more important chemical aspects of acidification of the soil is an increased mobilization of metals. When metals accumulate on the forest floor, many are bound up in organic compounds, or chemically bonded to the soil mineral fractions. In these forms metals are largely unavailable and will have little effect on plant roots. However, as the pH of soil decreases (becomes more acid) many metals lose their affinity for the organic ligands or minerals and become suspended in soil solutions. In these forms they are available to biological organisms, including tree roots, and begin to inhibit metabolic function.

Wet Tropics

The forests in the wet tropics vary from evergreen rain forests where growth occurs all year long, to deciduous rainforest with annual wet–dry cycles where growth is curtailed during part of the year. The seasonality of growth affects the extent of air pollution damage and the type of damage likely to occur. Many publications have highlighted the enormous diversity found in tropical forests, both within individual forest types, and globally when comparing rainforests of the world. One of the initial effects of acute air pollution toxicity is a loss of diversity. A few plant species are capable of tolerating the assault and ultimately prosper at the expense of less tolerant species. Whether this loss of diversity is a permanent or transient condition is subject to debate.

Air Pollution Causes

The tropics are generally defined as those areas between the tropic of Cancer (20° N) and the tropic of Capricorn (20° S). This climate zone covers most of South America, Africa, and parts of Southeast Asia and Oceania; thus many developing nations are found in the wet tropics. This section focuses on forest ecosystems where precipitation far exceeds evapotranspiration. Inland areas and landscapes along the western coasts of large continents, which tend to be arid or semiarid, will be discussed under that category. The wet tropics have relatively low industrial activity and traditional agricultural practices are small compared to many European nations. However, this is changing in many regions, and several examples of industrial pollution as well as effects of agricultural practices are beginning to be recognized. Urbanization and air quality problems associated with overcrowding and poor sanitation have created serious human health problems, but little research on ecological effects has been conducted. The use of fire as a land management tool and the prevalence of open fires for cooking, sanitation, and industry are the best-documented pollution concerns.

Air Pollution Concerns

Perhaps the most serious concern for the wet tropical regions is the potential for developing nations to repeat the environmental mistakes made by the developed world. At the same time developing nations are concerned that global air pollution problems of industrialized nations should not hinder their own efforts to improve the standard of living associated with industrialization. As has historically occurred in North America and Europe, when nations move from agrarian-dominated societies to urban manufacturing-based societies rapid influxes of people into cities causes crowding and sanitation problems. Until the necessary infrastructures are built, human and domestic animal wastes create nitrogenous pollutants and open fires remain the primary source for cooking and heating. Individually, small residential and entrepreneurial enterprises have little effect on the environment but, collectively, uncontrolled emissions from these sources generate the same air pollutants seen in larger industrial and urban complexes. These enterprises can produce sulfur dioxide, nitrogen oxide, and organic carbon compounds as primary pollutants. Secondary pollutants, nitric and sulfuric acids, aerosols and ozone generated by atmospheric processes are transported into adjacent forests or become part of the global circulation of anthropogenic atmospheric contaminants. Ammonia and other gases from poor sanitation, cropping systems, and animal husbandry resulting in nitrogen deposition and aerosol formation are typical of urban pollution problems anywhere in the world. The common use of managed fire, and the suggestion that wild fires have increased due to global climate change, are among the more serious concerns for sustainability of the unique forest structures in the wet tropics.

Air Pollution Effects

Clearly, burning to remove vegetation alters the immediate landscape but the effects of smoke on ecosystems downwind have only recently been addressed. The huge fires in Southeast Asia during the late 1990s and the annual burning of the cerrado grasslands in central Brazil offer examples of intentional and unintentional fire effects on native forests. Serious increases in tropospheric ozone have been documented as a result of cerrado fires. Concentrations measured are equivalent to those measured outside large urban centers (100–200 ppb). Data that document greatly increased atmospheric concentrations of volatile organic carbon and other pollutants due to the fires in Borneo have been published, but the long-term effects of these fires are not known. Few studies have been published relating the increase in ozone (and presumably other fire emissions such as organic carbon, nitrogen, and NO), to responses of native tropical forest trees, but experience from western North America would suggest that fire-generated ozone and its precursors are capable of being transported hundreds of kilometers, affecting native ecosystems far removed from the original burn site. Because the growing season is nearly year-round, foliar gas exchange would be expected to occur year-round as well, providing sites of entry for any number of airborne pollutants. The effect of anthropogenic emissions on the unique plant species of tropical rainforests is unknown. However, extrapolating from temperate forests where the nonvascular mosses and lichens appear to be the sentinel species, composition and structural changes are most likely occurring.

Semiarid Forests

Typically, forests found in semiarid regions are sparsely vegetated with trees and understory species well adapted to low, or seasonal water availability. Precipitation patterns vary from distinctly seasonal such as the wet winter/dry summer patterns of the Mediterranean climate, to bimodal rainfall patterns of wet winters and monsoon summer rains. On average, precipitation amounts equal evapotranspiration demands of the vegetation, but periodic drought is a normal feature. Forested landscapes are often at higher elevations where heat loads are not as intense and orographic processes increase total precipitation as moist air moves upslope. Many of these forests are found in coastal Mediterranean regions of the world where coastal influences modify the intense aridity found inland; southwestern North America, parts of the western coast of Africa and South America and of course, around the Mediterranean sea itself contain semiarid forests. Semiarid forests can be found inland as well, particularly at higher elevations where monsoonal rains provide enough moisture to survive the summers. Because metabolic activity is dependent on water and water availability is highly seasonal, direct interactions with the canopy and uptake of atmospheric pollutants are thought to be seasonal. However, deposited pollutants that accumulate in the terrestrial environment may result in unpredicted ecological responses.

Air Pollution Causes

These regions often contain extensive irrigation agriculture and large urban centers along shorelines focused on trade. Where logging has occurred it is not unusual for the forests to be extremely slow in returning, and total conversion of vegetation type to shrublands has been historically documented throughout the world. Although exceptions exist, for the most part semiarid regions do not contain large industrial complexes. Therefore both urban (primarily transportation sources) and agricultural pollutants are the most serious pollution causes in adjacent forested lands.

Air Pollution Concerns

The warm sunny climates, copious exhaust from roadways, and both natural and anthropogenic sources of volatile organic carbon provide the perfect combination for synthesis of the secondary pollutants ozone and nitric acid and primary and secondary aerosols. Nitrogen oxide and nitrogen dioxide from automobile exhaust can be taken up through leaf stomata but, except in the most extreme conditions, have only minor effects on plants. Because photochemical reactions that create ozone and nitric acid require sunlight, distinct diurnal patterns of atmospheric concentrations are typical. In coastal communities ozone concentrations may be near zero at night, increasing during the daylight hours to highs in the 100–400 ppb range. Since both ozone and the precursors are subject to transport aloft, similar ambient concentrations may be measured many kilometers away. This has been well documented in coastal southern California and southern Spain. Nitric acid is a byproduct of ozone synthesis. Currently there are no instruments that can measure nitric acid exclusive of other nitrogenous pollutants on an hourly basis. This has limited the ability to establish patterns of ambient concentrations and distribution. Denuder systems and passive collectors currently provide the best ambient concentration information, but they are labor-intensive and require longer exposure times. Therefore, the results are an integrated value over a 12-hour to 1-week period. Twenty-four-hour average concentrations above 1 ppb are considered high pollutant episodes. Daytime concentrations in the 10–12 ppb range have been recorded in southern California. Nitric acid is highly reactive. Once formed it can solubilize in water vapor, and readily deposit on exposed surfaces, combining with volatile ammonia products from cropping and animal production facilities to form ammonium nitrate aerosols.

Anthropogenic sulfur emissions are generally low in these regions largely due to the lack of significant coal-burning and metal-smelting operations but, along the coast and in saline valleys, natural sources of sulfate can provide the counterion for ammonium sulfate particles. Fugitive dust from roadways and land-disturbing operations such as construction and cropping practices are serious issues in these climates because the arid environment permits longer suspension times and therefore longer travel distances before the dust is deposited.

Air Pollution Effects

Ozone effects on semiarid forests are well documented in the Mediterranean climates of south-western North America, southern Spain, and Italy. Short-term exposures to ozone concentrations greater than 150 ppb can cause acute damage symptoms on many plant species. Long-term, chronic exposures to 50 ppb result in reduced growth of sensitive species and foliar mottling of many forest tree species. The primary sites of uptake and injury are the stomata of actively photosynthesizing leaves. When the stomata are open for gas exchange, ozone readily gains access to the stomatal cavity and mesophyll of foliage. Once inside the plant leaf, damage to cell and organelle membranes occurs, although the exact mode of attack is not well understood. Symptoms first appear as chlorotic spots on leaves and needles. As the damage progresses, cells in the chlorotic areas die, leaving necrotic spots. Although this kind of damage can be confused with other biotic and abiotic effects, the patterns of ozone damage and the distribution patterns of damage are often quite specific within a particular plant species. However, the lack of visible symptoms is not always an accurate indicator for tolerance to high ambient ozone concentrations. Ozone toxicity by itself is rarely the cause of death in mature trees, but weakens trees so that they are susceptible to insect, pathogen, or environmental assaults.

Much of the nitrogen deposition in semiarid forests occurs in the dry form, unlike nitrogen deposition in temperate regions. Dry deposition is very difficult to measure using current techniques. Among the many difficulties in understanding the effects of dry deposition is that nitrogen is a normal part of the ecosystem, unlike ozone or heavy-metal pollutants. For this reason establishing nitrogen deposition as a causal agent for changes in forests has been difficult. Deposited nitrogen accumulates during the dry season and becomes available when precipitation returns, in effect behaving as a fertilizer. Changes in nitrogen fertility have been shown to change ecological structure and function. Although forests are slow to respond to changes in fertility, monitoring nitrogen-impacted forests has indicated changes in species composition, beginning with the shorter-lived species, such as annuals and herbaceous perennials. Nitric acid and ozone are formed through the same photochemical processes in the atmosphere. Therefore, the presence of one is usually indicative of the other. Studies suggest that there is an interaction between the two air pollutants, but the nature of that interaction is poorly understood. Under some conditions it appears that nitrogen deposition may ameliorate ozone effects while under other conditions dry deposition of nitric acid to foliage may exacerbate ozone damage. The study of multiple pollutant effects is an emerging topic that will ultimately improve our understanding of air pollution effects on natural ecosystems.

Particulate pollutants occur in all parts of the world, but the low humidity and seasonal rainfall make suspended particulates a serious issue in semiarid ecosystems. The sizes of these pollutants can range from a few angstroms to several micrometers in diameter. The size affects physical behaviors such as travel distance and deposition as well as the pollutants' effects on biological organisms. Very small particles (less than 0.2 μm in diameter) are a serious public health concern. When breathed, they become lodged in the lung tissue and are not easily removed. It is not known whether similar phenomena occur in the plant kingdom. The effects of particulate pollutants in forests fall into two categories: physical abrasion/coatings and chemical effects. Blowing dust scratches leaf surfaces and damages the cuticles of leaves, increasing opportunities for pathogen infection. In addition, when dust lands and collects on foliage it blocks penetration of sunlight, reducing photosynthetic capacity. From a chemical standpoint, particulates serve as nutrient sources. Small ammonium nitrate or sulfate particles are capable of traveling hundreds of kilometers within a few days. Particles greater than 10 μm are restricted from rapid long-distance transport due to gravitational forces, but studies in Southwest North America have shown that multiple transport events over the course of a season can make a substantial contribution to the nutrient load at many kilometers distance from the particle source.

Temperate Forests

Most of the world's industrialized nations are partially or entirely in temperate climate regimes. Forests in the temperate climates experience all the air pollution insults and effects enumerated under other climate regimes. Ozone, particulates, nitrogen deposition, smoke, heavy-metal, and sulfur effects are well documented and in many ways best understood in these ecosystems. Europe and Central Asia have long histories of human settlement and industry. North America and Australia are more recently urbanized, but all participated in the industrial revolution that initiated large-scale air pollution effects in natural ecosystems.

Modern agricultural practices have improved crop yield and increased animal production by improving efficiency of land use. In many cases modern practices have led to highly concentrated animal husbandry operations where hundreds or thousands of animals are confined to small spaces and to the heavy use of synthetic fertilizers and pesticides. At the same time, urbanization concentrated humans into crowded cities where sanitation, fuel combustion for heating and cooking, and the need for transportation generates concentrated pollutants.

During the early expansion of industry and production agriculture, the ability of natural ecosystems to absorb the byproducts of human activities was either ignored or thought to be limitless. However, in the last several decades, many nations have recognized the serious effects of air pollution on forests and have taken steps to reduce or eliminate many of the pollutants through legislation and technology. Reduction in sulfur emission in the industrialized mid-west and northeastern parts of North America has resulted in measurable reductions in ambient concentrations and deposition to adjacent forests. Improved metal-smelting technologies have greatly curtailed atmospheric deposition of heavy metals in Canada, Europe, and parts of Asia. Improvements in energy production efficiency for heating, cooking, and transportation have reduced urban smoke emissions when compared to the air quality at the turn of the century. However, the problems of air pollution effects in temperate forests are far from solved.

Air Pollution Causes

The temperate forests are found in the most heavily populated climate zones on earth. All the known causes of air pollution are here. Intense animal production in western Europe, southeastern USA, and the UK produces enormous quantities of ammonia vapor that are then transported into native forests. Pesticide applications in valleys drift into the slopes of adjacent forests, and automobile exhaust continues to be one of the most serious causes of air pollution. Although reduction in sulfur emissions is a partial success story, nitrogen oxide emissions remain steady in the USA and are rising dramatically in western Europe and Asia as increased wealth allows increased numbers of automobiles and reliance on internal combustion engines for transport and energy production. Many of the most destructive smoke stack sources in Eastern Europe have been eliminated or reduced due to economic and outside pressure; however, these sources continue to impair forests seriously in developing Asian nations.

Air Pollution Concerns

The air pollution concerns of temperate regions are complex and intertwined. Frequently, it is difficult to isolate independent pollutant sources in an effort to control emissions and reduce impacts. Generation of the precursors for ozone synthesis, nitrogen oxide, and volatile organic carbon is a good example. Any combustion process – agricultural, urban, or industrial – can generate nitrogen oxide, although automobiles are the most frequently noted sources. Volatile organic carbon compounds can come from restaurants or dry cleaners, smoke stacks or motors, and fires or production of volatile compound by native vegetation. Once these compounds are aloft and the photochemical process initiated, the ozone created can impact forests tens or hundreds of kilometers away. This is clearly the case in the checkerboard pattern of land uses in the eastern half of the USA, much of Europe, and increasingly in Asia.

Pollution concerns in temperate agricultural systems are similar to those found in semiarid systems: particulates, nitrogen deposition, and pesticides. Unlike the semiarid systems, wet deposition plays a much more significant role. While wet deposition helps reduce high ambient particulate loads, it is the major source of nitrogen deposition in forests. The eutrophication effects of ammonia deposition are particularly acute in forests adjacent to large feedlots, dairy operations, and confined poultry and pig farms. Urban pollutant sources are generally associated with combustion processes, automobiles, and energy generation and its use. Although sanitation continues to be a problem in regions experiencing rapid population growth, many established urban centers have developed the necessary septic and sewer systems so that human waste is not generally an issue. Industrial waste does continue to impact local and global air quality. For many of the traditional smoke stack pollutants, sulfur, metals, and smoke particles, technology is available to reduce atmospheric loading; however, as new industries are being developed, new pollutants, particularly organic solvents, are emerging as serious health and ecological concerns. These new pollutants will continue to require new methods for detection and research into long-term impacts.

Air Pollution Effects

Acid rain and wet deposition are not unique to temperate forests but, because of milder temperatures, wet deposition, including fog and mists, can have pronounced effects on temperate ecosystems. Any substance that will solubilize in water will deposit as wet deposition. Acid rain studies have focused primarily on sulfuric and nitric acids but ammonia, metals, and pesticides – among other compounds – can be found in rain. One exception is ozone. Rainfall and very high humidity found in fog tend to ameliorate ozone, and without sunlight the chain reactions that form ozone are broken. The acidity in rain is caused by the presence of positively charged hydrogen ions (protons), which is why nitric and sulfuric acids have the most pronounced effect on pH; both are strong acids, releasing protons when solubilized in water. Normal rainfall tends to be slightly acidic, generally in the 6.2–6.5 pH range (neutral pH is 7). Acid rains have been measured as low as 3.5 and rainfall in the 4.5–5.0 ranges are not unusual in heavily industrialized or urban areas. How acid rain affects the forest is dependent upon many factors. In forest soils that are weakly buffered, wet deposition can reduce the soil pH, substantially changing below-ground processes, including mobilizing metals. Aluminum is an element that is found in large quantities in soils, but it is generally not toxic at higher pHs. When the pH is lowered, the availability of aluminum is increased, causing stunting of roots. Where soils are richer and better buffered, the percolation of rainwater through the soil profile leaches base cations (plant nutrients with positive charges) out of the rooting zone, causing impoverishment of the soil. The ability of forest soils to repair the damage once acid rain ceases is also highly dependent on the forest. Highly productive landscapes may reverse decline within a few years; however, many examples exist where the atmospheric inputs are no longer present, but the effects continue.

Wet deposition to foliar surfaces can result in erosion of the leaf surface. This is less of a problem in deciduous forests than in the evergreen conifer forests where excessive damage to needles results in premature abscission. Wet deposition of nitrogenous pollutants may not necessarily result in pH shifts, but long-term studies of nitrogen-affected forests indicate shifts in forest function and composition. The tendency of pollution-impacted forests to suffer 'winter kill,' for example, has been attributed to increases in nitrogen to those forests.

Remediation

Forests are slow to respond to management activities, and remediation measures are designed to shift the trajectories of forest ecological processes rather than completely change ecological patterns. Prescribed fire is being used as a remediation tool for several desired outcomes. Fire reduces the biomass of smaller trees and understory vegetation reducing the competition for water in semi-arid, ozone-impacted forests. Fire also reduces nitrogen loading in forests approaching nitrogen saturation and eutrophication. Selective harvesting and replanting of resistant varieties can also help shift pollution-impacted, declining forests into more productive forests. However, in recent years forests have demonstrated a surprising ability to recover all by themselves once the pollutant source is eliminated.

In recent years forests have demonstrated a surprising ability to recover once the pollutant source is eliminated. What was once thought to result in total destruction of forests in highly polluted regions is now understood to be yet another disturbance similar to fires or floods from which forests will recover over time. There are exceptions, such as sites heavily contaminated by metals; these areas will require more active remedial action. However, the annihilation of native forests due to air pollution, predicted during the 1970s and 1980s, has for the most part not occurred. Are these recovering forests the same before and after high pollution events? Probably not, but all landscapes are constantly responding to environmental conditions in ways that are difficult to quantify. It becomes the job of the forester and society to determine how air pollution effects are moderated so that all the resources that forests have to offer remain intact.

See also: **Environment**: Carbon Cycle; Impacts of Elevated CO_2 and Climate Change. **Genetics and Genetic Resources**: Genetic Aspects of Air Pollution and Climate Change. **Health and Protection**: Biochemical and Physiological Aspects; Diagnosis, Monitoring and Evaluation. **Site-Specific Silviculture**: Reclamation of Mining Lands; Silviculture in Polluted Areas.

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Carbon Cycle

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Introduction

The forest environment carbon cycle can be viewed at a number of scales. Measurements can be made at the scale of an individual leaf or tree, stand-scale measurements can be made, and models can be developed that examine forest-level, regional, and global carbon cycles. The role of the forest in the global carbon cycle has become increasingly important as it is realized that forests and forestry have a role to play in mitigating the so-called greenhouse effect. This article examines the sources, sinks, and fluxes of carbon as they relate to forests and then places this information within the context of global change. Finally, the potential contribution of forests to the mitigation of climate change is assessed.

The Global Carbon Cycle

The main components of the natural global carbon cycle are the sources, sinks, and fluxes between the land, oceans, atmosphere, and geological reservoirs. Current estimates suggest that the atmosphere contains about 730 Pg C, the land 2000 Pg C, the oceans 38 000 Pg C, and that an unknown amount remains in geological reservoirs. The greatest natural flux (120 Pg C per year) is between the land and the atmosphere, with a smaller flux occurring between the atmosphere and the oceans (90 Pg C per year). Estimates of the sizes of the different carbon pools are given in **Table 1**. In terms of fluxes, the carbon cycle can be seen as an approximate balance between the processes of photosynthesis by plants and respiration by plants, animals, and microbes. It is the variations on either side of an exact balance between photosynthesis and respiration that cause natural variations in the global carbon pools, supplemented by anthropogenic activities, such as the clearing of forests and the burning of fossil fuels,