Air Pollutant Deposition and Its Effects on Natural Resources in New York State

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Cover photograph courtesy of Barry Baldigo.

This book is dedicated to all of the air pollution effects scientists I have worked with over the past three decades to better understand the environmental impacts of air pollution in New York. You are too numerous to list and I would undoubtedly omit some inadvertently. You know who you are. I have learned a great deal from our collaborations and interactions and it has been great fun.

Thank you!

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Preface

A power plant somewhere between Pittsburgh and Chicago releases gasses and particulates into the air; they contain mercury, oxides of sulfur, and oxides of nitrogen. A busy nearby highway is lined with cars on their morning commute; each vents nitrogen from its tailpipe. A livestock feeding operation smells faintly of ammonia. Tens, or maybe hundreds, of miles downwind a fish lays dying in a streambed after a large rainstorm. Sugar maple in a northern hardwood forest look unhealthy, show signs of canopy dieback, and are no longer producing seedlings. The forest is changing. A loon is suffering from neurotoxicity, the result of eating too many fish containing too much mercury. Atmospheric pollutant emissions and eventual biological damages are linked. We know this. The scientific community has been studying it for more than 30 years. But between the gas and particle emissions and the unhealthy trees and fish, stuff happens. It involves transportation and transformation, meteorology, physics, chemistry, biology, and ecology. Soils and rocks buffer atmospheric acidity, nutrient cycles are disrupted, inorganic mercury is converted to its highly toxic methylmercury form that is prone to bioaccumulation, and aluminum is mobilized from soil to drainage water, where it poisons tree roots and fish. This book is all about that stuff in the middle, between cause and effect.

Air pollution in New York and elsewhere in the eastern United States began to increase in a serious way more than a hundred years ago. The amounts of sulfur, nitrogen, and mercury that we put into the air increased rather steadily, reaching peak values during the last quarter of the twentieth century. As the scientific community and then the general public have come to understand the human health and ecological price we were paying for the right to pollute, emissions have declined, especially in response to federal legislation such as the Clean Air Act and its amendments. For the most part, these pollutant levels have continued to decline. Nevertheless, legacy effects remain. As chemical and in some cases biological conditions improve, the scientific community is trying to better understand how low pollution emissions need to go. How good is good enough? What are the ecological, economic, and societal trade-offs? How should we manage our resources? This book will help readers develop an understanding of the complexities and begin to answer such questions.

Air pollution in the form of sulfur, nitrogen, and mercury is emitted from a wide variety of sources. These include power plants, motor vehicles, agriculture, incinerators, and industrial facilities. These pollutants are carried with the prevailing winds and are eventually deposited to the earth's surface in the form of precipitation, air particles and gasses, mountain clouds, and fog. Once deposited to vegetation or soil surfaces, they move into the soil water, where they can become adsorbed and stored on soil, taken up by plants and soil microbes, or leached to surface waters. Effects in the soil, vegetation, and surface-water ecosystem compartments are varied. A multitude of chemical and biological transformations occur, altering the chemical characteristics of the deposited substances and their behavior in the environment. Key processes relating to elemental cycling, toxicity, and bioaccumulation in the food chain vary with contaminant type. Ecological impacts are diverse. Depending on the severity of impact, trees may die, plant species composition may change, fish may be eliminated from a particular body of water, estuaries may become overenriched with nutrients, or a potent neurotoxin may bioaccumulate in fish, which in turn might be consumed by and have adverse impacts on fish-eating wildlife and humans. The costs to individuals and society are diverse and often substantial.

Adverse effects on lakes and streams and their watersheds occur throughout sensitive regions of New York. Pollutants can impact water quality and harm many species of aquatic biota. They also alter the chemistry of watershed soils, a process that has potential impacts on plant roots and other terrestrial life forms. Scientists study the biogeochemistry of the entire landscape. The chemistry of drainage water integrates a host of terrestrial and aquatic processes that interact with water as it moves from the atmosphere as precipitation through the soil and into the groundwater and eventually to streams, lakes, rivers, and estuaries. Thus, study of the water can elucidate processes on the terrestrial side.

This book describes these interactions and others. Here I summarize the collective experience of researchers who have been studying the effects of air pollutants on soils, waters, and associated biota in New York and across the United States for the past three decades. This book is targeted to students and practitioners of environmental science, water and air pollution, soil science, biogeochemistry, water resources, and aquatic and terrestrial ecology and to water resource professionals and other scientists and natural resource managers.

A host of questions revolve around and depend upon the study of air pollution and its effects. What lakes are acid-sensitive or acid-impacted? Is a stream limited in its primary productivity by nitrogen or something else? Have mayflies, zooplankton, or fish been impacted by too much acidity? If so, which species? Are forest tree distributions and forest health changed by atmospheric nitrogen or sulfur input? Has mercury bioaccumulation affected piscivorous wildlife such as loons, eagles, and mink? What is the critical load of air pollution that sensitive downwind resources can tolerate without unacceptable damage? What level of damage is acceptable? What have been the effects of air pollution on aquatic and terrestrial food webs? Are water-quality, soil, and forest conditions getting better, staying the same, or getting worse over time? The questions are endless. If you have questions such as these or if you want answers that you can base policy or management on, this book can be of assistance.

The focus is on air pollution effects in New York. I highlight, in particular, research results generated in the Adirondack and Catskill Parks, Long Island Sound and associated coastal estuaries, and the Great Lakes region. However, I also draw extensively from research conducted elsewhere in the northeastern United States, throughout the country, and overseas. The principles described in this book are applicable to the study of air pollution and its effects globally.

The various examples that are provided here deal with studies of environmental effects from atmospheric deposition of acidifying, eutrophying, and neurotoxic air contaminants. However, the principles that are developed and illustrated here also apply to the study of other environmental issues besides atmospheric deposition of sulfur, nitrogen, and mercury. The cycles, processes, and transformations discussed in this book can also inform the study of agricultural, silvicultural, and urban pollutants; climate change; and other aspects of nonpoint- and point-source pollution. A reader who grasps the materials presented in this book will be well equipped to design, implement, and interpret many kinds of pollution effects studies.

I hope that the information presented here will help you design, conduct, and interpret environmental effects studies that will help all of us to better understand the impacts of human activities on ecosystem health. Armed with high-quality data and appropriate analyses, we can collectively move forward to reduce unacceptable human-caused impacts in an economically responsible fashion and protect and improve the quality of our natural resources for future generations.

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Acronyms and Abbreviations

AcidBAP	acid biological assessment profile
ADRP	Acid Deposition Reduction Program
Al	aluminum
Al^{3+}	elemental aluminum ion
Al_i	inorganic aluminum
Al^{n+}	aluminum ions, expressed as the sum of all cationic aluminum ions
Al_o	organic aluminum
$Al(OH)_3$, $Al(OH)_2^+$, and $Al(OH)^{2+}$	aluminum hydroxides
ALS	Adirondack Lakes Survey
ALSC	Adirondack Lakes Survey Corporation
ALTM	Adirondack Long Term Monitoring Program
AMNet	Atmospheric Mercury Network
ANC	acid-neutralizing capacity
AQRV	air-quality related values
ASSETS	Assessment of Estuarine Trophic Status
BAF	bioaccumulation factor
BGC	biogeochemical
C	carbon
Ca	calcium
Ca^{2+}	calcium ion
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
$CaCO_3$	calcite
CAIR	Clean Air Interstate Rule
CASTNet	Clean Air Status and Trends Network
Cl	chlorine
Cl^-	chloride
CMAQ	Community Multiscale Air Quality
CO_2	carbon dioxide
CWA	Clean Water Act
Δ, delta	difference; change
ELS	Eastern Lakes Survey
EMAP	Environmental Monitoring and Assessment Program
EPA	U.S. Environmental Protection Agency
ERP	Episodic Response Project
Fe	iron
F-factor	fraction of the change in mineral acid anions in solution that is neutralized by base cation release from the soil
H	hydrogen; hydrogen atom

H^+	proton, hydrogen ion
ha	hectare
HCO_3^-	bicarbonate anion
Hg	mercury
$HgCl_2$	mercury chloride
Hg(II)	divalent mercury
HNO_3	nitric acid
IA	integrated assessment
K	potassium
K^+	potassium ion
kg	kilogram
L	liter
LISS	Long Island Sound Study
LOAEL	lowest observed adverse effect level
LTM	Long Term Monitoring Project of the U.S. EPA
m	meter
MAGIC	Model of Acidification of Groundwater in Catchments
MDN	Mercury Deposition Network
MEA	Millennium Ecosystem Assessment
MeHg	methylmercury
meq	milliequivalent
μeq	microequivalent
μg	microgram
μmol	micromole
Mg	magnesium
Mg^{2+}	magnesium ion
N	nitrogen
n	number of observations
N_2	molecular nitrogen; nonreactive nitrogen
N_2O	nitrous oxide
NA	not available; insufficient data
Na	sodium
Na^+	sodium ion
NAAQS	National Ambient Air Quality Standards
NADP	National Atmospheric Deposition Program
NAPAP	National Acid Precipitation Assessment Program
NH_3	ammonia
NH_4^+	ammonium ion
NH_x	atmospheric reduced nitrogen; includes NH_3 and NH_4^+
NH_y	total reduced nitrogen
NO_2	nitrogen dioxide
NO_3^-	nitrate

NOAA	U.S. National Oceanic and Atmospheric Administration
NO_x	atmospheric oxidized nitrogen; sum of NO and NO_2
NPDES	National Pollutant Discharge Elimination System
N_r	reactive nitrogen
NRC	National Research Council
ns	nonsignificant
NSWS	National Surface Water Survey
NTN	National Trends Network
NYSBAP	New York State Biological Assessment Profile
NYSERDA	New York State Energy Research and Development Authority
O_2	molecular oxygen
O_3	ozone
OEC	overall eutrophic condition
OHI	overall human influence
P	phosphorus
pH	relative acidity
PHREEQC	model for soil and water geochemical equilibrium
PIRLA	Paleoecological Investigation of Recent Lake Acidification
pK_a	acid dissociation constant
PnET	Photosynthesis and EvapoTranspiration
PnET-BGC	Photosynthesis and EvapoTranspiration–Biogeochemical
PnET-CN	Photosynthesis and EvapoTranspiration–C, water, and N balances
PO_4^-, PO_4^{3-}	phosphate
ppm	parts per million
PSD	prevention of significant deterioration
$RCOO^-_s$	strongly acidic organic anions
RHR	Regional Haze Rule
S	sulfur
SAA	sum of mineral acid anion concentrations
SBC	sum of base cation concentrations
Si	silicon
SO_2	sulfur dioxide
SO_4^{2-}	sulfate ion
SO_x	sulfur oxides
SPARROW	SPAtially Referenced Regressions On Watershed Attributes
TIME	Temporally Integrated Monitoring of Ecosystems
WATERSN	Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen
ww	wet weight
YOY	young of the year (fish)
yr	year

Air Pollutant Deposition and Its Effects on Natural Resources in New York State

CHAPTER 1

Background and Purpose

1.1. ATMOSPHERIC DEPOSITION IN NEW YORK

New York is home to a wide range of plant and animal species that occupy a multitude of ecosystems, from the high peaks of the Adirondack Mountains to the southern Great Lakes and the estuaries and coastal waters of the Atlantic Ocean. New York's forests support wildlife and timber production and contribute clean water for human consumption and aquatic ecosystem health. Lakes and streams support fish and the life forms on which they feed and the predators that feed on them. Coastal waters and estuaries that include Long Island Sound, the Hudson River Estuary, and Raritan Bay provide diverse habitats for aquatic species and support fisheries economies. In addition to the ecologic and economic values and the ecosystem goods and services New York's ecosystems provide, they also attract millions of visitors to the mountainous, Great Lakes, and coastal regions each year.

The Adirondack and Catskill Mountains regions of New York contain many protected lakes and streams that are affected by air pollution. The Adirondack Park, in particular, has been the focus of extensive research and monitoring efforts for more than 30 years so that we can better understand the effects of air pollution. Surveys have been conducted of hundreds of streams and more than a thousand lakes. There have been investigations of short-term changes in water chemistry during periods of rain and snowmelt, studies of acidification processes, the development and application of mathematical models to predict the rate of future recovery as air pollution levels decline, studies to estimate the critical loads of atmospheric deposition required to protect sensitive resources, and periodic sampling of dozens of lakes for more than 30 years to document changes over time. Much is known about aquatic and terrestrial resource sensitivity and damage in these regions from atmospheric deposition of air pollutants. However, much remains to be learned.

Air pollution in the form of atmospheric deposition of sulfur (S), nitrogen (N), and mercury (Hg) has caused substantial damage to sensitive and valuable resources in New York. Additional damage might occur in the future if air pollution continues at relatively high levels. However, federal and state efforts over the past several decades to curb air pollution emissions from power plants, industry, and motor vehicles have resulted in a pronounced decrease in air pollution and atmospheric deposition of airborne contaminants in New York and elsewhere in the eastern United States. Hopes have risen among environmental scientists and policy makers that damaged resources will recover, and indeed some recovery has been documented.

Resources considered highly sensitive to the effects of atmospheric deposition of S, N, and Hg are not evenly distributed across New York. Some areas contain extensive sensitive resources; other areas contain few. Resource sensitivity also varies with respect to the types of effects. Resources sensitive to acidification are clustered largely in the Adirondack and Catskill Mountains. Acid sensitivity has also been documented in the Shawangunk region of the state. Sensitivity to nutrient enrichment from atmospheric N deposition occurs statewide, but concern is most heavily focused on coastal areas and the Great Lakes region. Sensitivity to Hg methylation occurs statewide but is most prevalent in areas containing abundant wetland vegetation. Figure 1.1 shows the locations in New York where some of these sensitive resources are located.

Resources in the Adirondack and Catskill Mountains have been damaged by acidic deposition caused by both S and N air pollutants. In fact, these regions are among the most sensitive and damaged in the United States. Sulfur and N have been contributed from the atmosphere to soil and drainage water, lowering the pH and causing chemical changes that affect the suitability of the soil and water for supporting sensitive species of algae, plants, and animals. Some of the species affected are especially important to the citizens of New York, including trout and other sport fish and sugar maple (*Acer saccharum*) and red spruce (*Picea rubens*) trees. Estuaries and marine coastal waters have been affected by overenrichment with nutrient N. Some of that N is deposited from the atmosphere, but other important sources include agricultural runoff and wastewater treatment facilities. Added N often acts to stimulate algal growth in estuarine and marine waters, leading to a cascade of deleterious impacts on coastal waters and the plants and animals that live there.

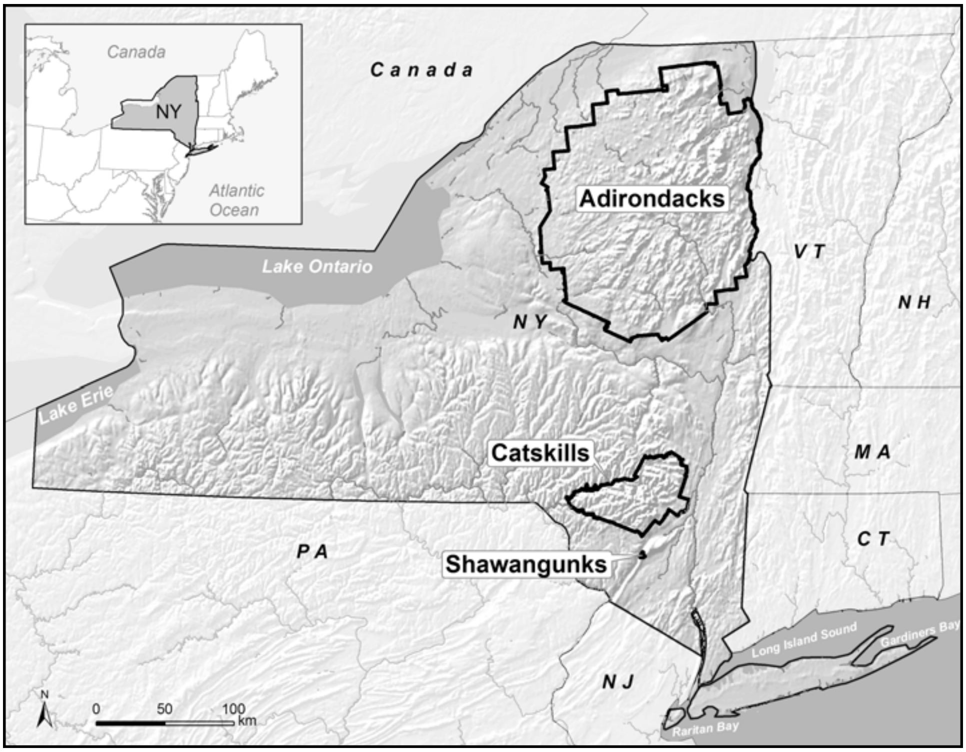

FIGURE 1.1. Locations of the major resources that are known to be sensitive to atmospheric inputs of sulfur, nitrogen, and mercury in New York: the Adirondack, Catskill, and Shawangunk regions; the Great Lakes; and coastal estuaries around Long Island.

Nitrogen deposition, especially to wetlands, meadows, and alpine environments, can alter competitive relationships among plant species and increase the establishment of nonnative species at the expense of some of the rare native species. Species shifts are thought to occur at N deposition levels as low as 5 to 10 kilograms per hectare per year (kg N/ha/yr) for raised and blanket bogs (Achermann and Bobbink 2003) and at even lower levels for alpine plant communities (Sverdrup et al. 2012). Some wetland plants are well adapted to low-N environments, including some species in the genera *Sphagnum* and *Isoetes* and some insectivorous plants, such as the green pitcher (*Sarracenia oreophila*) and the roundleaf sundew (*Drosera rotundifolia*). The pitcher plant (*Sarracenia purpurea*), a native of nutrient-poor peatlands in the eastern United States, has been proposed as an indicator of high atmospheric N supply (Ellison and Gotelli 2002).

Atmospheric deposition also contributes Hg to natural ecosystems in New York. When converted into a methylated chemical form, Hg bioaccumulates in food chains and is toxic to humans and wildlife predators. The latter include large fish, river otters (*Lontra canadensis*), mink (*Neovison vison*), loons (*Gavia* spp.), and bald eagles (*Haliaeetus leucocephalus*). There are also complex interactions between S and Hg deposition, because sulfate (SO_4^{2-})-reducing bacteria are believed to be the dominant source of methyl Hg (MeHg) in many natural ecosystems. By methylating Hg, these bacteria make it biologically available and facilitate biomagnification.

In response to atmospheric deposition of S, N, and Hg on New York ecosystems, fish, plants, and other life forms have suffered varying degrees of damage from acidification, nutrient enrichment, and toxicity. Citizens of New York have shown great concern about air pollution damage to brook trout (*Salvelinus fontinalis*) and other fish species. The general public may be less aware of effects on other life forms.

1.2. AIR QUALITY MANAGEMENT

1.2.1. Clean Air Act

The Clean Air Act (CAA) of 1970 was enacted to protect public health and welfare from the harmful effects of human-generated air pollution. Criteria pollutants are those for which the U.S. Environmental Protection Agency (EPA) has established National Ambient Air Quality Standards (NAAQS) as directed by the CAA. Standards were established for selected pollutants that are emitted to the atmosphere in significant quantities throughout the country and that may endanger public health and welfare. These include sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Although reduced N (NH_x) also contributes to these effects, standards have not been set for it. The primary NAAQS are designed to protect human health, while the secondary NAAQS are designed to protect public welfare from the adverse effects of pollutant(s). The CAA defines public welfare effects to include, but not be limited to, "effects on soils, water, crops, vegetation, manmade materials, animals, wildlife, weather, visibility and climate, damage to and deterioration of property, and hazards to transportation, as well as effects on economic values and on personal comfort and well-being."

The CAA as amended in 1977 also established the Prevention of Significant Deterioration (PSD) program. The primary objective of the PSD provisions is to prevent substantial degradation of air quality in areas that comply with NAAQS and yet maintain a margin for industrial growth. A PSD permit from the appropriate air regulatory agency is required to construct a new pollution source or substantially modify an existing source (Bunyak 1993). A permit application must demonstrate that the proposed polluting facility will (1) not violate national or state ambient air quality standards; (2) use the best available control technology to limit emissions; (3) not violate PSD increments for SO_2, nitrogen dioxide (NO_2), or particulate matter (PM); and (4) not cause or contribute to adverse impacts to air quality related values (AQRVs) in any Class I area. Class I areas include certain national parks and wilderness areas that receive the highest level of federal protection from air pollution damage. The PSD increments are allowable pollutant concentrations that can be added by industrial development to baseline concentrations.

The values Congress chose as PSD increments were not selected on the basis of concentration limits causing impacts to specific resources. Therefore, it is possible that pollution increases that exceed the legal Class I increments may not cause damage to Class I areas. It is also possible that resources in a Class I area could be adversely affected by pollutant concentrations that do not exceed the increments.

The following questions may be addressed when reviewing PSD permit applications:

- What are the identified sensitive AQRVs in each Class I area that could be affected by the new source?
- What are the air pollutant levels that may affect the identified sensitive AQRVs?
- Will the proposed facility result in pollutant concentrations or atmospheric deposition that will cause the identified critical level to be exceeded or add to levels that already exceed the critical level?
- If the critical level of the sensitive indicator is exceeded, what amount of additional pollution is considered "insignificant"?

The first two questions are largely land management issues that should be answered on the basis of management goals and objectives for the protected area. The last two are technical and policy questions that must be answered on the basis of analyses of projected emissions from the proposed facility and predictions of environmental response to given pollutant concentrations (Peterson et al. 1992).

In Title IV of the 1990 Clean Air Act Amendments (CAAA), Congress called for decreases in annual emissions of SO_2 and NO_x from utilities that burn fossil fuels. The legislation specifically required utilities to reduce (from 1980 levels) annual emissions of SO_2 by 10 million tons and annual emissions of NO_x by 2 million tons by the year 2010. As a consequence of Title IV, emissions and deposition of NO_x, especially sulfur oxides (SO_x), have declined substantially since 1990. The Clean Air Interstate Rule (CAIR) of 2005 further reduced S and N emissions and deposition, but that rule has gone through legal challenges.

The CAIR emissions control rule focused primarily on emissions controls on coal-fired electricity generating plants for the purpose of attaining NAAQS for particulate matter and ozone (O_3). However, the CAIR was challenged in court. The Cross State Air Pollution Rule (CSAPR) was scheduled to replace CAIR in 2012, but it too was litigated and vacated. In April 2014, the U.S. Supreme Court revised the earlier District of Columbia circuit court opinion that had previously vacated CSAPR. At the time of this writing, CAIR remains in effect but will probably be replaced by something different. It is not clear at this time what exactly will replace it.

1.2.2. Regional Haze Rule

More recent reductions in S and N emissions and deposition have been driven, in large part, by the need for states to comply with regulations aimed at improving visibility in Class I areas. The EPA promulgated regulations in 1980 to address visibility impairment that is "reasonably attributable" to one or a small group of sources. Congress subsequently added section 169B to the CAAA to focus attention on regional haze issues. On July 1, 1999, the EPA promulgated the Regional Haze Rule (RHR), which requires states (and tribes that choose to participate) to review how pollution emissions in the state affect visibility at Class I areas across a broad region (not just Class I areas in the state). These rules also require states to make "reasonable progress" in reducing any effect this pollution has on visibility conditions in Class I areas and to prevent future impairment of visibility. The rule requires states to analyze a pathway that takes the Class I areas from current conditions to "natural conditions" in 60 years. "Natural conditions," a term used in the CAA, means that no human-caused pollution can impair visibility. This program is aimed at Class I areas, which are not found in New York but occur in surrounding states (Plate 1). Thus, efforts to curtail emissions that impact Class I areas in nearby states also affect air pollutants that are emitted in or transported to New York. The RHR is improving regional visibility throughout the country and is noteworthy because the requirement to improve visibility will result in further decreases in S and N deposition. This is because ammonium sulfate is typically the principal contributor to haze at most locations in the eastern United States.

1.2.3. Federal Water Pollution Control Act

The Federal Water Pollution Control Act, commonly known as the Clean Water Act (CWA), was promulgated in 1972, and significantly amended in 1977, 1987, and 1990. The primary purpose of the act is to protect and restore the physical, chemical, and biological quality of the nation's waters. The act established the goals of making all navigable waters fishable and swimmable and eliminating the discharge of pollutants into the nation's waterways. Like the CAA, the CWA provides an additional tool to help states meet pollution control mandates. The impaired streams and anti-degradation sections of this law are pertinent to air pollution effects assessment because streams acidified by S and/or N deposition may qualify to be listed as impaired streams on what is known as the 303(d) list.

States manage and protect water quality under the CWA through the development and enforcement of ambient water-quality standards. Water quality standards are composed of three interrelated parts: (1) designated beneficial uses of a water body, such as contact recreation or cold-water fishery; (2) numerical or narrative criteria that establish the limits of physical, chemical, and biological characteristics of water sufficient to protect beneficial uses; and (3) an anti-degradation provision to protect water quality that exceeds criteria and to protect and maintain water quality in in waters designated as Outstanding National Resource Waters, an EPA category. States comply with water-quality standards by controlling the type and quantity of point-source pollutants entering waters through the National Pollutant Discharge Elimination System (NPDES) and by implementing best management practices for nonpoint sources of pollution. Section 303(d) of the act requires states to also formally identify waters that do not currently meet water-quality standards and bring them into compliance through the development and implementation of total maximum daily loads, which establish the maximum loadings of pollutants that a water body can receive from point and nonpoint (including atmospheric deposition) sources of pollution without exceeding the standards.

1.2.4. Other Legislation

New York State has enacted statewide emissions regulations for coal-fired power plants. The original law, the State Acid Deposition Control Act, was passed in the 1980s. A second law, the Acid Deposition Reduction Program (ADRP), was passed in 2004 that will require fossil fuel–fired electric generators in New York State to reduce NO_x and SO_2 emissions. Affected sources must reduce SO_2 emissions to 50 percent below the levels allowed by Phase 2 of the federal acid rain program. Affected sources must reduce NO_x emissions during the non-O_3 season (October–April) to a level that corresponds with the NO_x reductions that were achieved starting on May 1, 2003, through the implementation of the CAIR NO_x Ozone Season Trading Program for the O_3 season (May–September). Although these regulations do not address emissions from upwind states, they do contribute to the overall pattern of regional emissions controls that influence atmospheric deposition of S, N, and Hg at the locations of sensitive ecosystem receptors in New York.

1.3. ECOSYSTEM FUNCTIONS AND SERVICES

Ecosystem services refer to the fundamental value of ecosystems to human welfare. Ecosystems provide many goods and services that are critical for the functioning of the biosphere and provide the basis for the delivery of tangible benefits to human society. These include food, materials, pharmaceuticals, ecosystem processes and cycles, recreation, relaxation, and spiritual enrichment. Terminology regarding ecosystem services, human value, ecosystem function, and social benefit can be confusing (Table 1.1). ICSU-UNESCO-UNU (2008), The Millennium Ecosystem Assessment (MEA; 2005), and the EPA (2008) have defined ecosystem services to include supporting, provisioning, regulating, and cultural services:

- Supporting services support the provision of other ecosystem services through such actions as production of biomass, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provision of habitat.
- Provisioning services include products such as food, fiber, and medicinal and cosmetic products (Gitay et al. 2001).
- Regulating services include carbon sequestration; climate and water regulation; protection from natural hazards such as floods, water and air purification; and disease and pest regulation.
- Cultural services satisfy human spiritual, educational, and aesthetic needs and foster appreciation of ecosystems and their components.

TABLE 1.1. Key terms that are central to the ecosystem service concept based on the example of acidification effects on recreational fishing

Term	Description	Examples
Final ecosystem service	End product component of nature that yields human well-being	Sport fishery, surface water
Intermediate service	Intermediate product needed to support final ecosystem services	Water quality needed to support a sport fishery
Value	Importance to people, expressed in monetary or nonmonetary terms	Opportunity to fish in an aesthetically pleasing location that contains suitable sport fish
Function/process	Intermediate step that contributes to the service	Nutrient cycling, cleansing of drainage water as it flows through soil, microclimate regulation
Social benefit or source of well-being	Arises from the human use of an ES, often in combination with other conventional goods and services	Recreation, spiritual enrichment, relaxation, natural biodiversity maintained

In evaluating the effects of air pollutants on ecosystem services, each service should be geographically referenced and expressed where possible in generally comparable units of measure (Gimona and van der Horst 2007; Naidoo et al. 2008). This allows comparison of loss or gain in ecosystem services across space and across time. Services that can be measured and stacked to facilitate prioritization of key regions or watersheds are especially important to human well-being because key areas such as the Adirondack and Catskill Parks provide a multitude of services in proximity to centers of human population and provide services that are highly valued by the citizens of New York.

Regulating services include natural cycles and processes and the ways they benefit people. It is difficult to estimate their value. Cultural services include a variety of emotional, psychological, and spiritual benefits that humans derive from natural ecosystems; these are also difficult to quantify. Cultural services also include benefits related to outdoor recreation and ecotourism, which are important components of rural economies in New York. Such services include fishing, hunting, hiking, swimming, boating, and wildlife viewing. Sources of human well-being, ecosystem services, and the social benefits of ES are closely related (Figure 1.2).

However, many of the supporting and regulating services MEA (2005) and others have identified are inconsistent with a definition of ecosystem services that is measurable, mappable, and capable of being stacked and valued. There are also difficulties of double-counting of intermediate products or services when the value of one ecosystem service is embedded in the value of another ecosystem service. For example, supporting services, such as nutrient cycling, constitute intermediate services that should not be valued directly because they are already included in the process of assessing impacts on a final ecosystem service, such as provision of a trout fishery (Sullivan 2012).

Boyd and Banzhaf (2007) stress the importance of separating intermediate and final services for economic valuation. It is these final ecosystem services that satisfy the need to measure, stack, map, and assign value such services. Interim products, functions, processes, and cycles are intermediate to or contribute to final ecosystem services but are not themselves final services (Sullivan 2012). Given the importance of these considerations, and in keeping with the economic issues raised by Boyd and Banzhaf (2007), a final ecosystem service can be defined as follows:

> an endpoint component of nature that can be enjoyed, consumed, or used by people to generate human well-being and that can be measured, stacked, mapped, and valued using a common currency. (Sullivan 2012)

Resource management and public policy should focus in large part on these final ecosystem services, which are determined by the processes, cycles, and intermediate services that are the focus of ecological research.

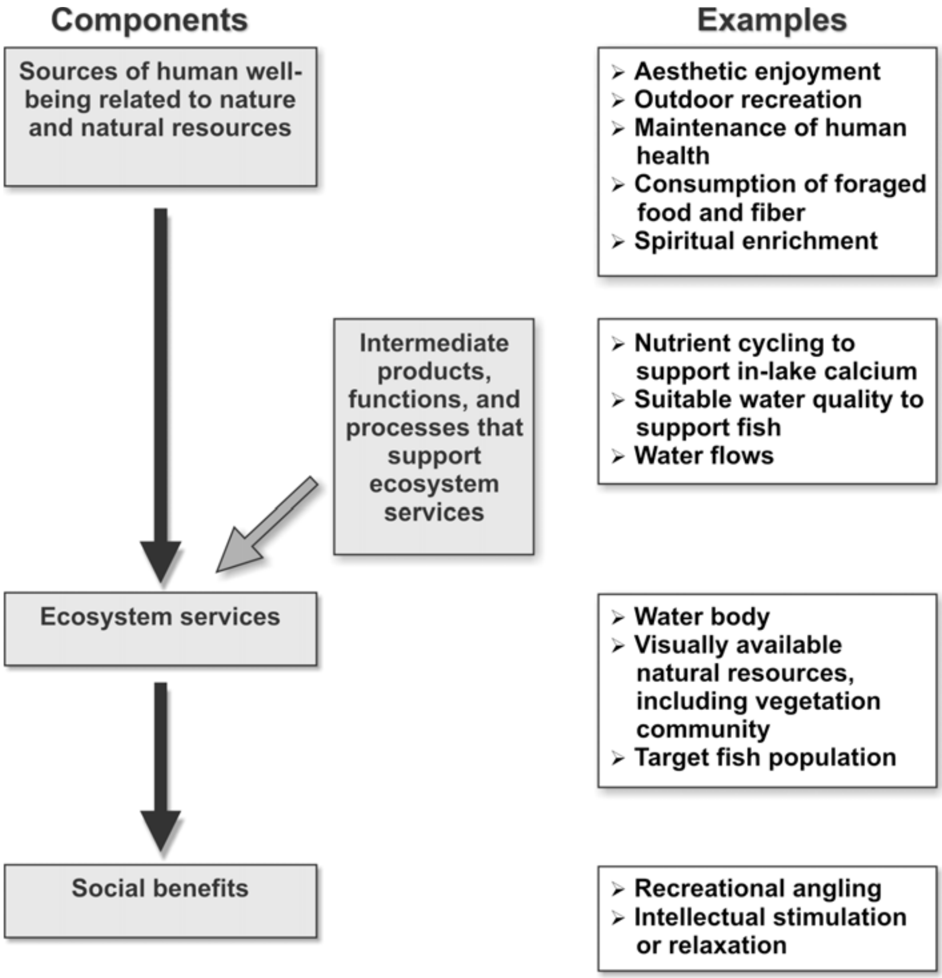

FIGURE 1.2. Relationships among sources of human well-being, ecosystem services, and social benefits that accrue from ecosystem services, using the example of recreational fishing. Adapted from Boyd and Banzhaf 2006; Sullivan and McDonnell 2012.

A decrease in ecosystem services is often reflected in economic loss. Determination of the net impact of changes in ecosystem services requires a complete accounting of costs and benefits using a common currency for valuation of ecosystem services. This is important because society and makers of environmental public policy will be less likely to ignore the consequences of air pollution and the benefits of mitigation if the economic costs and damages are clearly defined and are expressed in terms of monetary value. Restoration of ecosystem services that have been lost due to air pollution damage can affect a wide range of potential benefits to society (Table 1.2).

Calculation of a change in ecosystem services caused by an environmental stress such as acidification, Hg biomagnification, or nutrient enrichment must be based

TABLE 1.2. Anticipated ecosystem service benefits to be realized by moving from a state of critical load exceedance to non-exceedance in the Adirondack Mountains

Ecosystem service	Anticipated benefits	Notes
Provisioning services		
Production of maple syrup and related products	Continued or increased production of food products	Important regional benefit
Catch of brook trout and other game fish in sport fishery	Continued or increased catch of sport fish	Important regional benefit, especially in the Adirondack and Catskill Parks
Production of maple wood for furniture and other wood products industry	Continued or increased wood production	Limited benefit
Production of spruce wood for wood products	Continued or increased wood production	
Provision of wildlife habitats	Continued provision of habitat for species associated with sugar maple or red spruce trees or surface waters	Difficult benefit to quantify
Regulating services		
Climatic regulation	Decreased greenhouse gas production or increased carbon sequestration can reduce potential for climate warming impacts	Difficult benefit to quantify
Water regulation	Improved tree health in some habitat types can maintain or enhance water storage, reducing the impacts of flooding and providing increased stream flow during low flow periods	Difficult benefit to quantify
Erosion regulation	Decreased effect on vegetation cover can limit possible increases in erosion during heavy precipitation events	Difficult benefit to quantify