KEY FINDINGS

The main effects evaluated in the ISA are acidification, nitrogen enrichment and mercury methylation.

Acidification is driven by deposition of nitrogen oxides and sulfur oxides, and results in a cascade of effects that harm terrestrial and aquatic ecosystems, including slower growth and injury to forests, and localized extinction of fishes and other aquatic species.

Nutrient enrichment results from deposition of nitrogen oxides, along with other sources of reactive nitrogen (e.g., fertilizers, wastewater, and atmospheric ammonia deposition), and it causes a suite of ecological problems including biodiversity losses, disease, eutrophication, and harmful algal blooms.

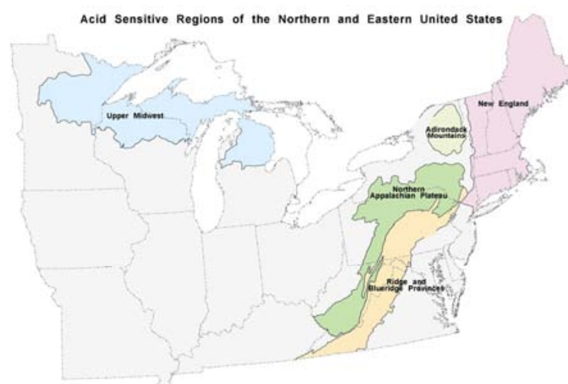
Particulate sulfate can interact with methanogenic bacteria to produce methylmercury, a powerful toxin that can bioaccumulate to toxic amounts in higher trophic levels (e.g. otters, and kingfishers).

This draft Integrated Science Assessment is a concise synthesis and evaluation of the most policy-relevant science to help form the scientific foundation for the review of the secondary (ecological or welfare-based) national ambient air quality standards for nitrogen oxides and sulfur oxides.

Ecological effects of acidification

Deposition of some nitrogen and sulfur species can cause acidification, altering biogeochemistry and affecting biota in terrestrial and aquatic ecosystems across the U.S. Major effects on biota include a decline in some forest tree species, such as red spruce and sugar maple; and a loss of biodiversity of fishes, zooplankton, and macroinvertebrates.

- The sensitivity of terrestrial and aquatic ecosystems to acidification from sulfur and nitrogen deposition is predominantly governed by surficial geology.
- Deposition of inorganic nitrogen and sulfur species routinely measured was as high as 9.6 kg N/ha/yr and 21.3 kg S/ha/yr, respectively, in the U.S. in 2004–2006.
- Areas most sensitive to terrestrial effects from acidifying deposition include forests in the Adirondack Mountains of New York, the Green Mountains of Vermont, the White Mountains of New Hampshire, the Allegheny Plateau of Pennsylvania, and high-elevation forest ecosystems in the southern Appalachians.
- Many of the most acid sensitive surface waters in the U.S. are in the Northeast (see figure below) and mountainous West.



Regions of the eastern U.S. that contain appreciable numbers of lakes and streams sensitive to deleterious effects from acidifying deposition. (Source: Stoddard et al., 2003)

Biogeochemical effects

Acidifying deposition alters biogeochemistry in terrestrial and aquatic ecosystems.

- In terrestrial ecosystems, ecological effects are linked to changes in soil chemistry, including soil base saturation, inorganic aluminum concentration in soil water, and soil carbon-to-nitrogen ratio.
- In aquatic ecosystems, ecological effects are linked to changes in surface water chemistry, including sulfate concentration, nitrate concentration, sum of base cations, acid neutralizing capacity, surface water

inorganic aluminum concentration, and surface water pH.

Examples of biogeochemical indicators of effects from acidifying deposition on ecosystems	
Ecosystem	**Biogeochemical Indicator**
Terrestrial	• Soil base saturation • Inorganic Aluminum concentration in soil water • Soil carbon-to-nitrogen ratio
Aquatic	• Sulfate • Nitrate • Base cations • Acid neutralizing capacity • Surface water inorganic Aluminum • pH

Biological effects

Acidifying deposition alters ecosystem structure.

- Biological effects of acidification in terrestrial ecosystems are generally linked to aluminum toxicity and decreased ability of plant roots to take up base cations.
- Decreases in acid neutralizing capacity and pH and increases in inorganic aluminum concentration contribute to declines in zooplankton, macroinvertebrates, and fish species richness in aquatic ecosystems.

Examples of biological indicators of effects from acidifying deposition on ecosystems.	
Indicator	**Measure**
Terrestrial ecosystems	
• Red spruce	• Percent dieback of canopy trees
• Sugar maple	• Dead basal area, crown vigor index, fine twig dieback
Aquatic ecosystems	
• Fishes, zooplankton, crustaceans, rotifers	• Presence/absence • Fish condition factor • Biodiversity

Ecosystems will continue to be acidified by current emissions. For example, in the Adirondacks, the current rates of nitrogen and sulfur deposition exceed the amount that would allow recovery of the most acid sensitive lakes. In the Shenandoah Mountains, historically deposited sulfate has accumulated in the soil and is slowly released from the soil into stream water where it causes acidification and makes parts of this region sensitive to current loading. Numeric models suggest that the number of acidic streams will increase under the current deposition rates.

Ecological effects of nitrogen deposition

Nitrogen deposition causes ecosystem enrichment and eutrophication that alters biogeochemical cycles and harms biota, such as native lichens, and alters biodiversity of ecosystems, such as grasslands and meadows. Nitrogen deposition contributes to eutrophication of estuaries and the associated effects including toxic algal blooms and fish mortality.

- Multiple forms of reactive nitrogen (e.g., ammonia, ammonium ion, nitrogen oxides, nitric acid, nitrous oxide, nitrate, urea, amines, proteins, and nucleic acids) contribute to the ecological effects of nitrogen enrichment. However, most ecological experiments have deposition data for only a subset of the total of reactive nitrogen chemical species.
- Deposition of inorganic nitrogen species was as high as 9.6 kg N/ha/yr in 2004-2006.
- At least one important component of N, ammonia, is not measured routinely in any national network, but may account for greater than 80% of total reduced nitrogen deposition.
- Existing monitoring networks are inadequate to characterize the full extent of regional heterogeneity in nitrogen and sulfur deposition, and very likely underestimate the total nitrogen deposition across wide areas of the U.S.
- Ecological effects can occur at nitrogen deposition rates as low as 2 kg/ha/yr.

Biogeochemical effects

Reactive nitrogen deposition alters the biogeochemical cycling of nitrogen.

- Atmospheric nitrogen deposition is the main source of new nitrogen to terrestrial ecosystems. The onset of nitrate leaching from soils is an indicator of excess nitrogen in these systems and is calculated to begin at values ranging from ~5 to 10 kg N/ha/yr for forests in the eastern U.S. Importantly, nitrogen deposition can profoundly affect ecosystems prior to the onset of nitrate leaching.
- The contribution of atmospheric nitrogen deposition to total nitrogen loads varies by wetland-type; freshwater bogs are the most sensitive, and salt marshes are the least sensitive. Nitrogen mineralization increases with nitrogen addition, which can increase nitrogen export from wetland to adjacent surface waters.
- Atmospheric nitrogen deposition is the main source of nitrogen to headwater streams, lower order streams, and high elevation lakes. Elevated surface water NO_3^- concentrations due to nitrogen deposition occur in both the eastern and western U.S.

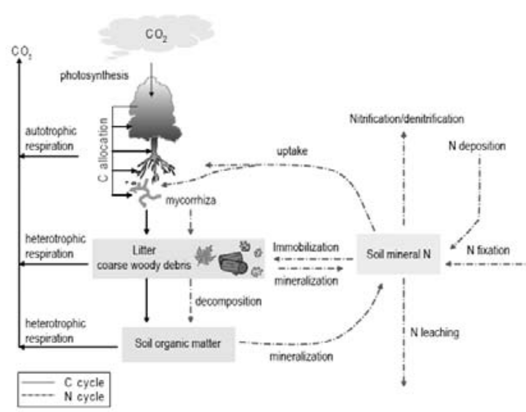
Examples of biogeochemical indicators of effects from reactive nitrogen deposition on ecosystems

Ecosystem	Biogeochemical Indicator
Terrestrial and Wetland	• NO_3^- leaching • Nitrification/denitrification • N_2O emission • CH_4 emission • Soil C: nitrogen ratio • Foliar/plant tissue [N], C:N, N:Mg, N:P • Soil water [NO_3^-] • Soil pore water [NH_4^+]
Freshwater and Estuarine Aquatic	• Chlorophyll a • Water [NO_3^-] • Dissolved inorganic nitrogen • Dissolved oxygen • N:P ratio

- The contribution from atmospheric nitrogen deposition can be greater than 30% of total nitrogen loadings in some of the most highly eutrophic estuaries in the U.S., including the Chesapeake Bay.

N deposition affects primary productivity, thereby altering biogeochemical cycling of carbon.

- Nitrogen deposition can accelerate plant growth and change carbon allocation patterns (see figure below), which can increase their susceptibility to severe fires, drought, and wind.
- Nitrogen deposition causes changes in ecosystem carbon budgets. However, whether nitrogen deposition increases or decreases ecosystem carbon-sequestration remains unclear. For example, a limited number of studies suggest that nitrogen deposition may increase carbon-sequestration in forests, but has no apparent effect on carbon-sequestration in non-forest ecosystems.
- Productivity of many freshwater ecosystems and most estuaries and coastal water ecosystems is nitrogen limited. Nitrogen deposition can cause eutrophication of aquatic ecosystems.



Interactions between the carbon and nitrogen cycles.

Methane and nitrous oxide are green house gases that have biogenic sources and sinks. Nitrogen deposition alters methane and nitrous oxide fluxes in terrestrial and transitional ecosystems.

- Nitrogen addition increases the flux of nitrous oxide from soils to the atmosphere in coniferous forests, deciduous forests, grasslands, and wetlands.
- Nitrogen addition can reduce methane uptake in coniferous and deciduous forest. In wetlands, nitrogen addition can increase methane production, but has no apparent effect on methane uptake.

Biological effects

Multiple biological indicators have shown that nitrogen deposition alters ecosystem structure.

- Addition of nitrogen to most ecosystems causes changes in primary productivity and growth of plants and algae, which can alter competitive interactions among species. Some species grow more than others, leading to shifts in population dynamics, species composition, and community structure. The most extreme effects include a shift of ecosystem type in terrestrial ecosystems, and hypoxic zones that are devoid of life in aquatic ecosystems, which typically results from nitrogen loading from multiple sources.

Examples of biological indicators of effects from nitrogen deposition on ecosystems

Ecosystem	Biological Indicators
Terrestrial and Wetlands	• Altered community composition, biodiversity and /or population decline. Taxa affected include: diatoms, lichen, mycorrhiza, moss, grasses and other herbaceous plants. • Plant root: shoot ratio • Terrestrial plant biomass/production
Aquatic	• Phytoplankton biomass/production • Toxic or nuisance algae blooms • Submerged aquatic vegetation • Fauna from higher trophic levels

Quantified relationships between deposition levels and ecological effects

- Lichens are the most sensitive terrestrial taxa to nitrogen with clear adverse effects occurring at 3 kg N/ha/yr in the Pacific Northwest and Southern California.
- The onset of declining biodiversity was found to occur at levels of 5 kg N/ha/yr and above within grasslands in Minnesota and in Europe.
- Altered species composition of Alpine ecosystems and forest encroachment into temperate grasslands was found at 10 kg N/ha/yr and above in both the U.S. and Canada. A brief list of deposition levels and associated effects is shown below.

Examples of quantified relationships between deposition levels and ecological effects

Kg N/ha/yr	Ecological effect
~1.5	Altered diatom communities in high elevation freshwater lakes and elevated nitrogen in tree leaf tissue high elevation forests in the U.S.
3.1	Decline of some lichen species in the Western U.S. (critical load)
4	Altered growth and coverage of alpine plant species in U.S.
5	Onset of decline of species richness in grasslands of the U.S. and U.K.
5.6 - 10	Onset of nitrate leaching in Eastern forests of the U.S.
5-10	Multiple effects in tundra, bogs and freshwater lakes in Europe (critical loads)
5-15	Multiple effects in arctic, alpine, subalpine and scrub habitats in Europe (critical loads)

Sulfate effects on mercury methylation

Mercury is highly neurotoxic and enters the food web in its methylated form. Because sulfate can stimulate bacterial production of methyl mercury, sediments and biota in wetlands and other aquatic ecosystems can have elevated concentrations of methyl mercury. In 2006, 3,080 fish advisories were issued in the U.S. due to the presence of methyl mercury in fish.