

Rooted in Research

Northern Research Station

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Managing Mercury: Insights from Monitoring and Manipulation at the Marcell Experimental Forest

Mercury is a persistent environmental pollutant emitted from fossil fuel combustion. It is widely dispersed in the environment and can be especially concentrated in peatlands. Peatlands provide many ecosystem services, such as carbon storage, water filtration, and wildlife habitat. However, environmental conditions in peatlands can be conducive to the formation of the highly toxic methylmercury that bioaccumulates in the aquatic food chain and leads to harmful health effects in humans, animals, and other fauna.

The mercury methylation process occurs in conditions that are low in oxygen, are high in available carbon, and contain sulfate-reducing or iron-reducing bacteria, all of which are found in peatland environments where mercury has accumulated for decades from emissions and subsequent atmospheric deposition.

In northern Minnesota, peatlands occupy about 30 percent of the landscape. Within this landscape lies the Marcell Experimental Forest, an outdoor laboratory for researchers from the U.S. Department of Agriculture Forest Service, Northern Research Station, and other institutions who study how mercury cycles through ecosystems and how human activities influence mercury levels. Three novel studies at the Marcell Experimental Forest, which include long-term monitoring and experimental manipulations, show the effects of pollution reduction and climate change on downstream movement of methylmercury.

Boardwalk into the S2 watershed at the Marcell Experimental Forest. USDA Forest Service photo by Jake Burdick.

KEY FINDINGS

- Methylmercury, a toxic form of mercury that moves easily through food webs, increases in stream water with the addition of sulfate, which can occur through sulfur emissions from human activities.
- Methylmercury spikes in stream water when sulfate increases, but it decreases rapidly—concentrations in stream water return to original levels within two years—when atmospheric sulfate pollution is reduced. Concentrations of methylmercury in aquatic organisms take longer than two years to recover.
- Although methylmercury in stream water has decreased over time because air quality has improved, warmer air temperatures caused by higher greenhouse gas concentrations and faster rates of decomposition and mercury cycling processes could reverse this trend.

Mercury Methylation in Peatlands

Although mercury enters the atmosphere naturally through events such as volcanic eruptions, human activities such as coal burning and industrial processes have increased mercury concentrations in the atmosphere by 450 percent globally compared to pre-industrial levels (c.a. 1450; Outridge et al. 2018). Once in the atmosphere, mercury circulates widely and can travel far from the original source. Mercury also enters waterways through mining, manufacturing, and municipal wastewater (Kolka et al. 2022).

Mercury transforms into methylmercury, one of the most toxic forms of mercury, under low-oxygen, or anaerobic, conditions. In this process, microbes add a methyl group to mercury, which consists of carbon and hydrogen. Methylmercury produced in headwater peatlands travels downstream and accumulates in the tissues of fish and other aquatic organisms. Concentrations of methylmercury can then build up through the food chain in a process called biomagnification. As methylmercury accumulates in living tissue and humans and other predators eat fish, it becomes a dangerous neurotoxin that damages nerve tissue. Pregnant women and children are especially susceptible to the negative health impacts of methylmercury, as well as other groups that consume fish or other seafood in large quantities.

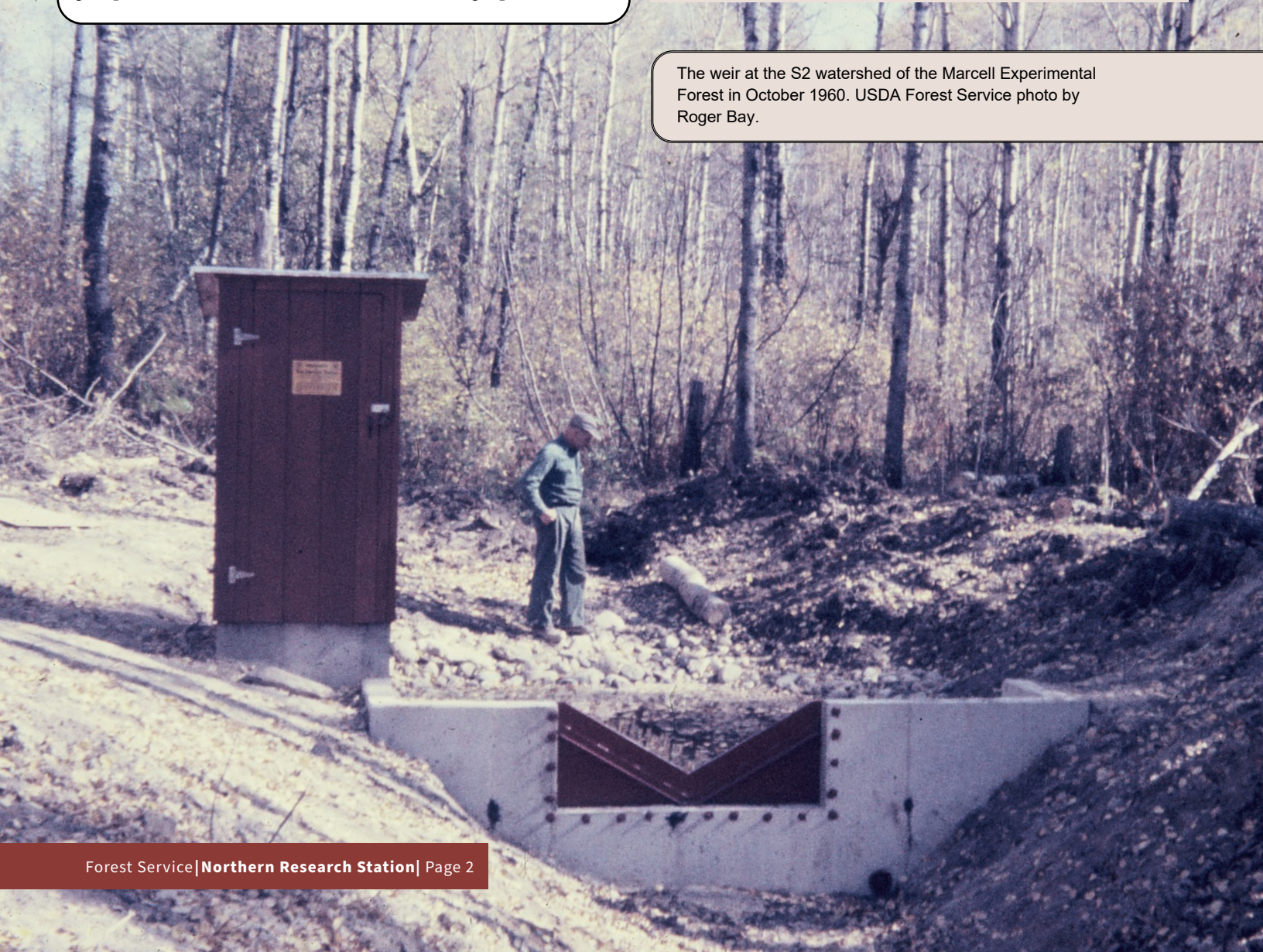
THE MARCELL EXPERIMENTAL FOREST

The Marcell Experimental Forest is one of the longest running peatland research programs in the world. Data collection began in 1960, and long-term datasets include nearly 65 years of data on streamflow, water table, soil water, and weather. The site consists of six watersheds, each containing at least one peatland.

Scientists who study the forest have written hundreds of publications on topics related to hydrology and nutrient cycling across a range of conditions, including two different types of peatlands: nutrient-poor bogs driven by precipitation inputs and nutrient-rich fens fed by groundwater. Because bog inputs are primarily from precipitation, they are much more susceptible to pollution deposition and extreme weather events such as droughts.

In 2024, the Marcell Experimental Forest received Wetland of Distinction status from the Society of Wetland Scientists for its ecosystem services and contributions to wetland science.

The weir at the S2 watershed of the Marcell Experimental Forest in October 1960. USDA Forest Service photo by Roger Bay.



METHYLMERCURY AND SULFATE DEPOSITION

- A long-term sulfate-addition study at the Marcell Experimental Forest demonstrated that increases in sulfate deposition results in higher methylmercury levels in stream waters.
- The study found that when sulfate deposition is reduced, methylmercury levels decrease rapidly, recovering to baseline levels within two years in stream water. The recovery is slightly longer for aquatic organisms.
- The results suggest that methylmercury levels in stream water and some aquatic organisms in peatlands can recover quickly from reductions in sulfur air pollution.



Irrigation systems installed throughout an experimental peatland watershed at the Marcell Experimental Forest supplied sulfate to simulate increased atmospheric sulfate deposition from 2001 through 2008. USDA Forest Service photo by Stephen Sebestyen.

Air Quality Effects on Methylmercury Formation in Peatlands

Results from a long-term sulfate-addition by [McCarter et al.](#)

Methylmercury production is closely linked to sulfate; the microbes that transform mercury into methylmercury use sulfate instead of oxygen in some of their metabolic processes. Sulfate is the by-product of industrial processes, such as coal burning, mining, and paper production, and from utilities and municipal wastewater (Kolka et al. 2022). And even though the Clean Air Act of 1970 has successfully reduced sulfur emissions in the United States since it was enacted, sulfate deposition in the eastern United States remains above pre-industrial levels (Benish et al. 2022). In the midwestern United States, industrial activities have increased sulfur concentrations in freshwater ecosystems (Kolka et al. 2022).

A long-term sulfate-addition experiment to a peatland on the Marcell Experimental Forest has demonstrated the link between mercury and sulfate and suggests that ecosystems can recover rapidly when sulfur emissions or point sources of sulfur from industry are greatly reduced. This watershed-scale study began in 2001 by simulating higher past levels of sulfate deposition (i.e., from the 1970s) to one hectare (2.5 acres) of a peatland through an irrigation system. Sulfate addition continued through 2006. Between 2006 and 2008, one-third of the sprinklers used to irrigate the peatland and supply sulfate were turned off, and after 2008, sulfate was no longer applied to the peatland. Stream water flowing from the peatland and an adjacent, reference peatland was sampled for chemistry from

1998 through 2012, which encompasses the full sulfate-addition period as well as several years before and after sulfate addition.

The six-fold increase in sulfate deposition that was applied in the experiment led to a five-fold increase in flow-weighted methylmercury concentrations in stream water compared to the reference watershed. When sulfate deposition ended, methylmercury concentrations in stream water and at least one type of aquatic organism (mosquito larvae) decreased sharply. Stream water concentrations of mercury decreased most quickly, returning to baseline levels, but mosquito larvae still had slightly elevated mercury two years after sulfate deposition was stopped. Total mercury concentrations were more than two times higher in mosquito larvae in the sulfate-addition treatment than in the control, but were 1.4 times higher in mosquito larvae in the "recovery" treatments, where sulfate deposition was stopped early (Coleman Wasik et al. 2012).

The results show a direct connection between sulfate levels and methylmercury formation and that ecosystems can recover quickly when sulfur emissions are reduced, though recovery may be slower in aquatic organisms. They also imply that air quality standards, such as those imposed through the Clean Air Act and amendments, can reduce ecosystem methylmercury levels and thereby reduce neurotoxin exposure through food webs.

Stream Water Methylmercury Decreases with Improving Air Quality

Results from a long-term monitoring effort by [McCarter et al.](#)

Mercury in stream water is influenced not only by air pollution but also by factors such as climate change. Rising air temperatures are expected to increase production of methylmercury by accelerating the process by which microbes transform mercury into methylmercury. But disentangling the effects of climate change and air pollution on mercury levels is difficult without long-term records of climate, stream water chemistry, and atmospheric deposition.

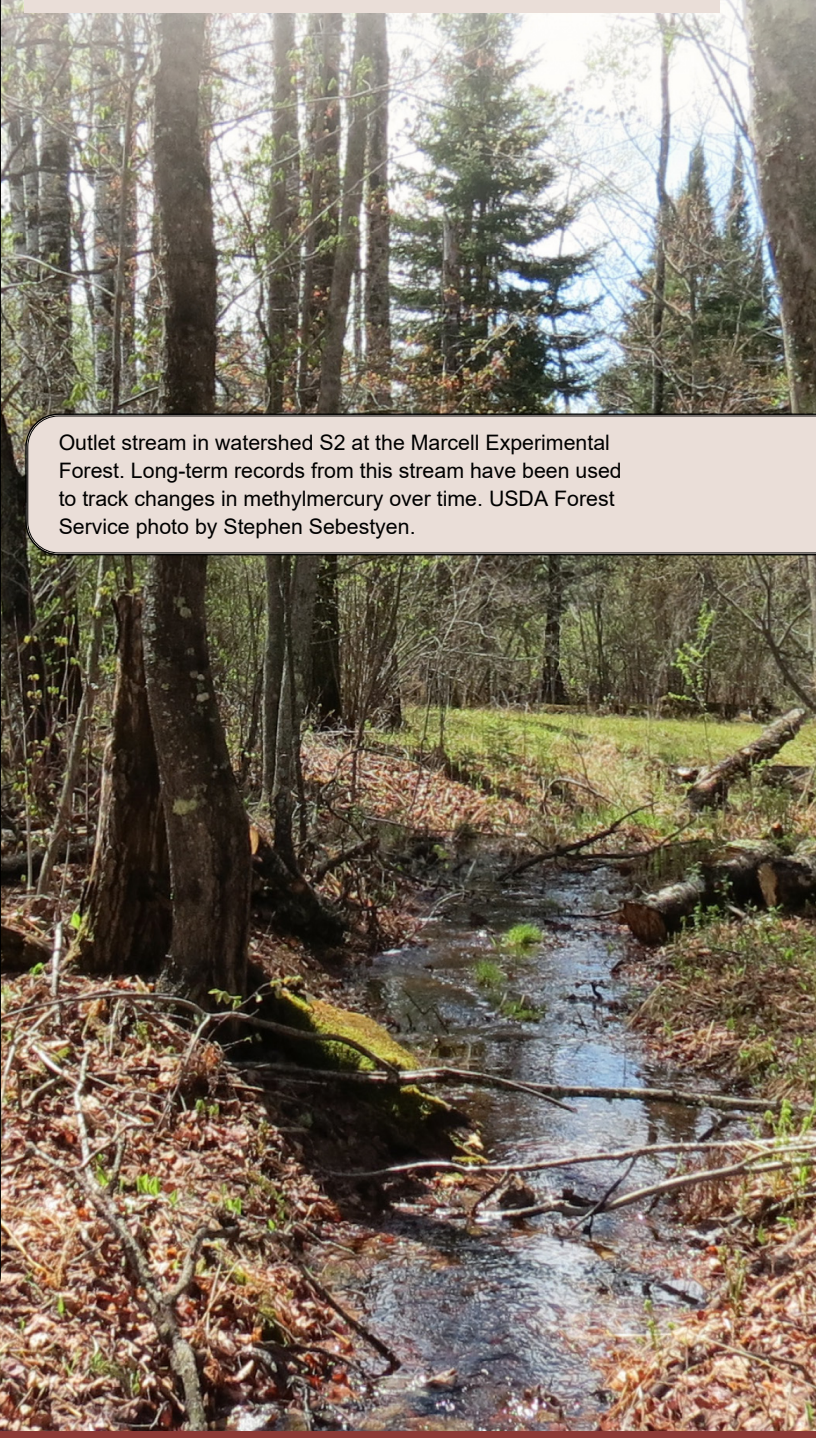
At the Marcell Experimental Forest, Northern Research Station scientists collaborated with researchers at Nipissing University, Gustavus Adolphus College, and the University of Minnesota to determine whether mercury has decreased as air quality has improved over time amidst concurrent changes in climate. The Marcell Experimental Forest has 17 years of data on stream water methylmercury concentrations—an unprecedented record—as well as a long-term hydrology and climate record spanning 55 years and a dataset measuring atmospheric deposition of mercury over 21 years. Together, these records allowed the research team to produce the first watershed-scale observations showing how both total mercury and methylmercury exports from peatlands change with the interacting effects of cleaner air and climate change.

Methylmercury levels in stream water were positively correlated with mercury deposition from the atmosphere, which decreased over 17 years. Methylmercury was also related to the runoff ratio, which means that as relatively less precipitation becomes streamflow due to increasing air temperatures that induce ecosystem drying, less methylmercury was transported from the peatland. During that same period, however, the researchers found that methylmercury levels increased as air temperatures increased.

The observations and analyses from the long-term records at the Marcell Experimental Forest show that water quality improves as atmospheric pollution decreases. That is, less methylmercury flows downstream from peatlands when atmospheric pollution is reduced. Atmospheric mercury deposition is currently near pre-industrial levels, however, because of decades of elevated deposition watershed soils are still high in mercury that is available for methylation and downstream bioaccumulation in the food chain. With increasing air temperatures, methylmercury levels could reverse and start to increase over time. But because methylmercury levels are also influenced by the runoff ratio, which is also influenced by air temperature, it remains to be seen exactly how watershed transport of methylmercury will change in the future.

LONG-TERM MERCURY RECORDS IN STREAM WATER

- Long-term records at the Marcell Experimental Forest show that methylmercury and total mercury concentrations have decreased in stream water over time, which is consistent with a decrease in atmospheric mercury deposition.
- Methylmercury levels in stream water have decreased over time despite an increase in air temperature, which would be expected to increase methylmercury levels.
- As air quality has improved and reached pre-industrial levels, effects of climate change on methylmercury may have a greater influence, and methylmercury levels may increase.



Outlet stream in watershed S2 at the Marcell Experimental Forest. Long-term records from this stream have been used to track changes in methylmercury over time. USDA Forest Service photo by Stephen Sebestyen.



An open-top enclosure used to simulate the effects of warming and elevated carbon dioxide on peatland ecosystems in the SPRUCE experiment. USDA Forest Service photo by Stephen Sebestyen.

Changes in Methylmercury with Climate

Results from an experiment with ecosystem warming and higher CO₂ concentrations reviewed by [Kolka et al. 2024](#).

SPRUCE (Spruce and Peatland Responses Under Changing Environments) is an ecosystem-scale manipulation study on the Marcell Experimental Forest funded by the U.S. Department of Energy and a collaboration between Oak Ridge National Laboratory and the USDA Forest Service designed to help scientists disentangle the combined climate change effects of CO₂ and warming on peatland ecosystems.

Ten open-topped enclosures rise 7 meters (23 feet) above the peatland, each with a different temperature and CO₂ concentration combination. Treatments include one of five warming levels (0, 2.25, 4.5, 6.75, and 9 °C higher than ambient temperature) combined with either ambient or increased air CO₂ concentrations (~500 parts per million higher than ambient levels during the growing season).

Eight years of mercury measurements in SPRUCE have yielded the following findings:

- Warmer air temperatures increased methylmercury concentrations in peatland soil water, which ultimately feeds into stream water. Rising air temperatures could have increased peat decomposition rates, which in turn could have released more methylmercury from soils into downstream waters.
- Warmer temperatures were found to increase net gaseous fluxes of mercury. Although increases in mercury gas fluxes might reduce the amount of methylation that can happen in one area, these fluxes

increase the potential for mercury to be redistributed elsewhere, which spreads the risk of mercury methylation to new locations.

- Elevated CO₂ concentrations were associated with high methylmercury levels in peatland soil water. Carbon dioxide is not known to directly influence the formation of methylmercury, but other changes to physical or peat chemical properties that are influenced by CO₂, such as changes in water table levels or decomposition rate, could indirectly influence methylmercury levels.

The SPRUCE results suggest that both warming and CO₂ concentrations are associated with release of more methylmercury to water, with alarming consequences for downstream water quality, wildlife, and human health.

SPRUCE FINDINGS AT A GLANCE:

Methylmercury in Peat under Warming and Increased CO₂

- Warmer air temperatures led to increases in methylmercury in peatland soil water, which makes it available for downstream transport.
- Higher CO₂ concentrations increased methylmercury in peatland soil water.
- Net gas fluxes of mercury increased with warming, which can decrease methylation potential of mercury locally but redistribute mercury to other areas where it can be converted to methylmercury and enter new waterways.

Summary of Recent Mercury Studies on the Marcell Experimental Forest

Monitoring and manipulation at the Marcell Experimental Forest have shown that

- sulfate is tightly correlated with methylmercury production, and peatland ecosystems can recover quickly from reductions in sulfate deposition,
- methylmercury production is influenced by both air quality and the higher air temperatures associated with climate change, and
- ecosystem warming and elevated CO₂ concentrations both influence methylmercury release.

The results of these studies show how experimental manipulations and long-term monitoring complement each other to tell a fuller story of mercury in peatlands and the factors that influence methylmercury production and release. These studies show that lower stream water methylmercury concentrations are directly linked to reduced deposition of atmospheric pollutants. However, caution is warranted because mercury remains in the landscape from past emissions. The improvements observed in the long-term record may reverse if effects of environmental warming lead to greater release of methylmercury from the landscape and outpace effects of reducing emissions and deposition.

Bog in S1 watershed at the Marcell Experimental Forest. USDA Forest Service photo by Stephen Sebestyen.

SCIENTISTS

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The Marcell Research Center at the Marcell Experimental Forest. USDA Forest Service photo by Jake Burdick.

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