Science
FINDINGS

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"Science affects the way we think together."

Lewis Thomas

Sour Streams in Appalachia: Mapping Nature's Buffer Against Sulfur Deposition
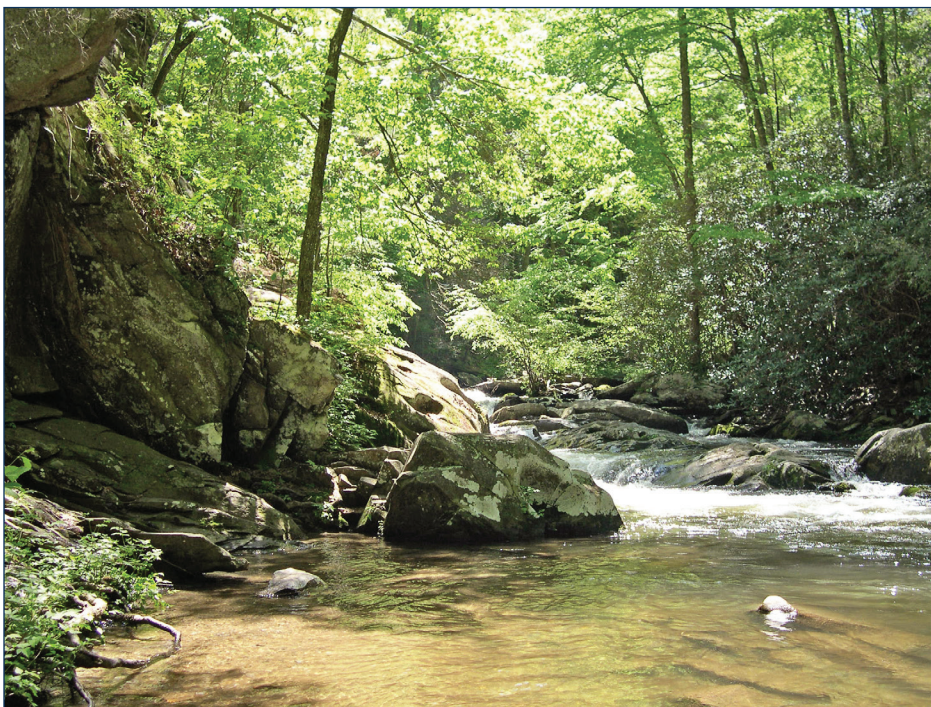
Cheryl Devlin

Sulfur emissions are regulated by the Environmental Protection Agency, but sulfuric acid that has leached into soil and streams can linger in the environment and harm vegetation and aquatic life. Some watersheds are better able to buffer streams against acidification than others; scientists learned why in southern Appalachia. Above, a stream in the Cherokee National Forest.

IN SUMMARY

Even while emissions are in decline, sulfur released into the air primarily by coal- and oil-burning power plants continues to acidify streams in the eastern United States, stressing vegetation and harming aquatic life. Watersheds rich in base cations—nutrients that attract and bind acidic molecules—naturally buffer streams against acidification. These watersheds can be identified by their soils, vegetation, and other physical properties.

Mitigating stream acidification depends on knowing how much sulfuric acid falls on a landscape over time, but also on accurate predictions of base cation weathering (BC_w) rates in watersheds. However, previous models lack the accuracy to predict BC_w rates across large regions. Accurate predictions are needed to inform policy and management decisions.

Using a machine learning approach, scientists with the U.S. Forest Service Pacific Northwest Research Station developed a model that predicts and maps BC_w rates in the southern Appalachian Mountains. The model made better predictions than traditionally used linear regression methods, and confirmed many findings of prior empirical studies. The study also found that BC_w rates were influenced by other climatic variables, such as precipitation and temperature. Results are being used to support sulfur critical loads modeling throughout the region.

"I believe that there is a subtle magnetism in Nature, which, if we unconsciously yield to it, will direct us aright."

—Henry David Thoreau

S ay the words "acid rain," and you get mixed reactions. Maybe a blank stare as someone imagines ghastly images of melting umbrellas and singed flesh. Those old enough, remember hearing it during the late 1970s and into the 1990s. And, they remember learning, with some relief and embarrassment, that it wasn't quite the zombie apocalypse they'd imagined. Others recall that acid rain is vaguely connected to dirty air.

But say "acid rain" to someone who has visited or lived near the southern Appalachian Mountains, and they have stronger memories. These include images of dying spruce and fir trees, conversations about dead trout in mountain streams, or hiking amidst smog-obscured vistas anywhere in the rugged chain of mountains and valleys from Georgia to Pennsylvania.

Acid rain and dirty air were big news. Heavy smog from factories and power plants lingered in the Appalachian skies. The haze was so bad it reduced visibility in the Smoky Mountains from 90 miles to 20 miles. "People don't realize that at times, the air quality is actually worse in the park than where they came from," reporters quoted a Park Service scientist in 1996. Researchers and the public were only beginning to understand the connections between the smog, dead fish, the dying trees, and rain sometimes as acidic as vinegar.

Since then, scientists have confirmed that power plants typically burning coal release sulfur into the atmosphere, which turns into sulfuric acid by the time it settles on the ground. It falls not just as acid rain, but also as snow or as dry particles. Sometimes it hangs near mountain ridges, aloft in acidic clouds. Or it hugs the ground in acidic fog.

But scientists have also realized that some landscapes have built-in buffers against acidity. Certain watersheds are rich in calcium, magnesium, potassium, or sodium: base nutrients that can neutralize acids and help plants grow. Streams flowing from some of these watersheds can remain healthy in spite of current or future acid rain or snow events. Watersheds that don't have a lot of these nutrients are sitting ducks.

KEY FINDINGS ☞ ☜

- The model reduced error rates by nearly half, compared to linear regression models.

- It confirmed established relationships between base cation weathering (BC_w) rates and watershed soils, geology, sulfur deposition, and vegetation conditions.

- BC_w rates were also influenced by other climatic variables such as precipitation and temperature.

- The model predicted low BC_w in watersheds whose parent material was high in silica; received little precipitation; had soils that were low in clay, nitrogen, and organic matter; and had low to moderate forest cover.

- BC_w drivers were consistent across the study area, except for the central Appalachians, where high sulfur deposition and unique geology and climate may influence predictions.

Acting on a request by the Environmental Protection Agency (EPA), Forest Service scientists Keith Reynolds, Paul Hessburg, and Nicholas Povak built new computer models to identify these vulnerable watersheds in the Southern Appalachian Mountain Region. The area is home to a captivating array of species, including native brook trout, bog turtles and black bears, and encompasses seven national forests and two national parks. Streams and rivers, including the New River, the oldest river in North America, descend from high mountain peaks and rocky outcrops.

"The EPA and the national forests want to know—when and where mitigations are needed—before the fish and the bugs that they eat are in trouble," Hessburg says. To accomplish this, the researchers are trying out new predictive modeling techniques that combine computer algorithms, artificial intelligence, and brute data crunching.

WANTED: BASE CATIONS

*T*he heart of the project concerns base cations, another name for nutrients that have the power to neutralize acids. When rocks weather and become soil, they release certain elements and minerals that can either be acidic or basic. "For example, basic compounds come from limestone," Hessburg says. "Calcareous deposits release calcium and other minerals that can neutralize acids."

The scientists wanted to map the rates at which base cations break down and are released into soils and streams in the southern Appalachians. The process, called base cation weathering or BC_w, is one of the most important yet difficult to estimate parameters in calculating a landscape's critical load. When an area's critical load of sulfur deposition is surpassed, harmful effects begin to take a toll on the environment.

Scientists traditionally estimate BC_w by collecting stream and soil samples, analyzing their chemical composition, and running the data through complex computer models. These "process-based" models require a large amount of field-collected data and long processing times, and they provide predictions that are only relevant to the individual watersheds where the data were collected. This

Bill Jackson

A technician collects a water sample from the Cherokee National Forest that will be tested for levels of sulfuric acid.

USDA United States Department of Agriculture

Forest Service

makes the analysis of a region as big as the southern Appalachian Mountains both time-consuming and a costly process. But, resource managers need to make decisions about large landscapes, not just individual watersheds.

Recently, scientists have quantified the statistical relationships between process model estimates and environmental data, which are readily available across large geographic areas. These relations can be used to predict BC_w rates across the region. Initial models used a statistical analysis approach called linear regression, which models the relations between two variables by fitting a linear equation to the observed data.

Povak says, "If your response variable is BC_w rate and your environmental driving variable is the percentage of watershed area dominated by siliceous (silica bearing) bedrock, which contributes little to BC_w, then a linear model assumes that BC_w rates decrease in a linear fashion with increased percent siliceous bedrock."

Unfortunately, relations between environmental variables can be nonlinear and complex. And indeed, the researchers found that the relationship between BC_w rate and siliceous bedrock was nonlinear. "When you have low levels of a siliceous rock, you can get really high levels of BC_w, but up to a point," Povak says. "When you hit about 15 percent, you see a huge decrease in BC_w rates. After this threshold is reached, the effect of additional silica on reducing BC_w rates is minimal." When you model complex relationships with linear regression, you can get errors. Sometimes, very large errors.

A final challenge the researchers ran into was in the data sampling. "There was a lot of data in locations where people expected that native fish and aquatic insects might be in trouble; local knowledge was quite good," Hessburg says. "But there was much less data in areas where people did not expect to find problems. From a statistical prediction perspective, this imbalanced sampling can complicate model prediction. Ideally, you want to have data relatively well distributed across a sampled region."

There was a wealth of observed stream, soil, and atmospheric deposition data from other studies, taken from 140 different watersheds in the region. The researchers derived BC_w rates for these watersheds using the process-based **M**odel of **A**cidification of **G**roundwater **i**n **C**atchments (MAGIC). They now needed a new model that would take this data, and combine it with data from the rest of the region's geography, climate, and sulfur deposition, to generate a continuous map of BC_w rates for the rest of the region's watersheds.

South Appalachian brook trout thrive in fast-moving, cold water streams. The region's brook trout populations were severely reduced in the early 1980s. Sulfur leaching into mountain streams made the water too acidic for the fish.
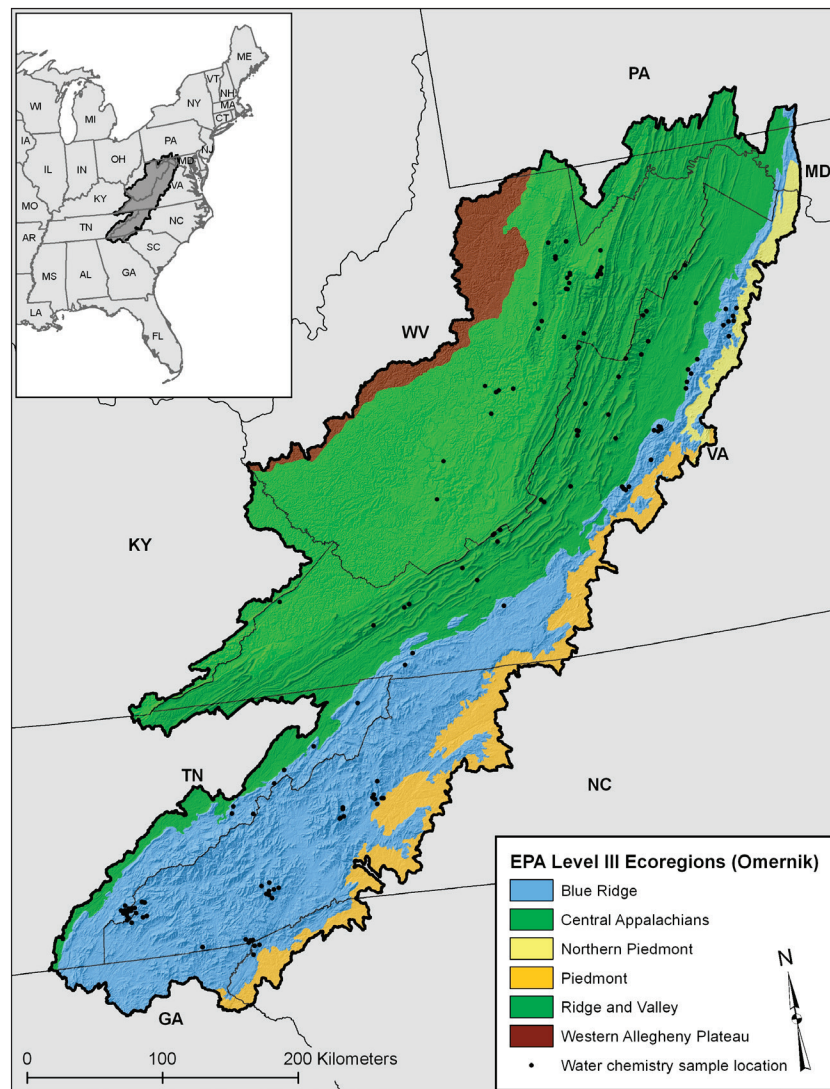
This figure shows the locations of base cation weathering (BC_w) sample points in the southern Appalachian Mountains. Forest Service scientists used the BC_w data to develop a model that maps out BC_w rate predictions over the whole area; information needed by resource managers.

MACHINE LEARNING

*T*o accomplish this, the researchers used an approach called machine learning, a kind of automated reasoning relatively new to ecological research. The approach involves the construction of computer algorithms that can learn from the patterns detected in data. The algorithms are used to build a model from example inputs, and this resulting model is used to make predictions. Because Reynolds (a research forester), Hessburg, and Povak (research ecologists) were not experts in atmospheric or stream water chemistry, they relied on colleagues who were experts to help them refine their algorithms.

The researchers pitted several conventional linear regression models against machine learning models. They used BC_w rate as the response variable, and aspects of the underlying geology, soils, geomorphology, climate, topography, and acidic deposition rates as predictor or driving variables.

They found that the machine learning algorithms were flexible and could model all types of relationships and interactions among the variables—something that the linear regression models were quite poor at. "Linear regression models are very powerful in the right applications, but they assume that you have these very linear relationships between variables," Povak says.

Statistical models that could capture the complex nonlinear relationships between sulfur deposition and environmental variables in this case did a better job of identifying sensitive ecosystems. Because of this flexibility, the machine learning models reduced error rates by nearly half. "That was a real breakthrough for us," Povak says. The machine learning approach also addressed their less-than-ideal data sampling, and they were able to identify zones of high uncertainty that resulted from low sampling.

Their model results confirmed other studies on established relationships between BC_w rates and watershed soils, geology, sulfur deposition, and vegetation. For example, low BC_w rates were predicted in watersheds whose parent material was high in silica, a compound low in base cations. Low rates were also predicted in small watersheds, with naturally acidic soils, that were low in clay, nitrogen, and organic matter, and watersheds with low to moderate forest cover.

They also found that BC_w rates were influenced by other climatic variables such as precipitation and temperature, and this result was intuitive. Rain speeds up weathering in soils and rocks. Warmer temperatures speed up chemical reactions and soil respiration. Overall, the models found that BC_w rates across much the southern Appalachian Mountains were inherently low.

"The statistical modeling went through an indepth comparison of about a half dozen modeling techniques, to see which one would produce the best modeling result with the lowest error rate," Hessburg says. "It took several years to get all the products through the assembly line." In the end they chose the random forest model, which performed the best, to successfully map BC_w rates in the study region.
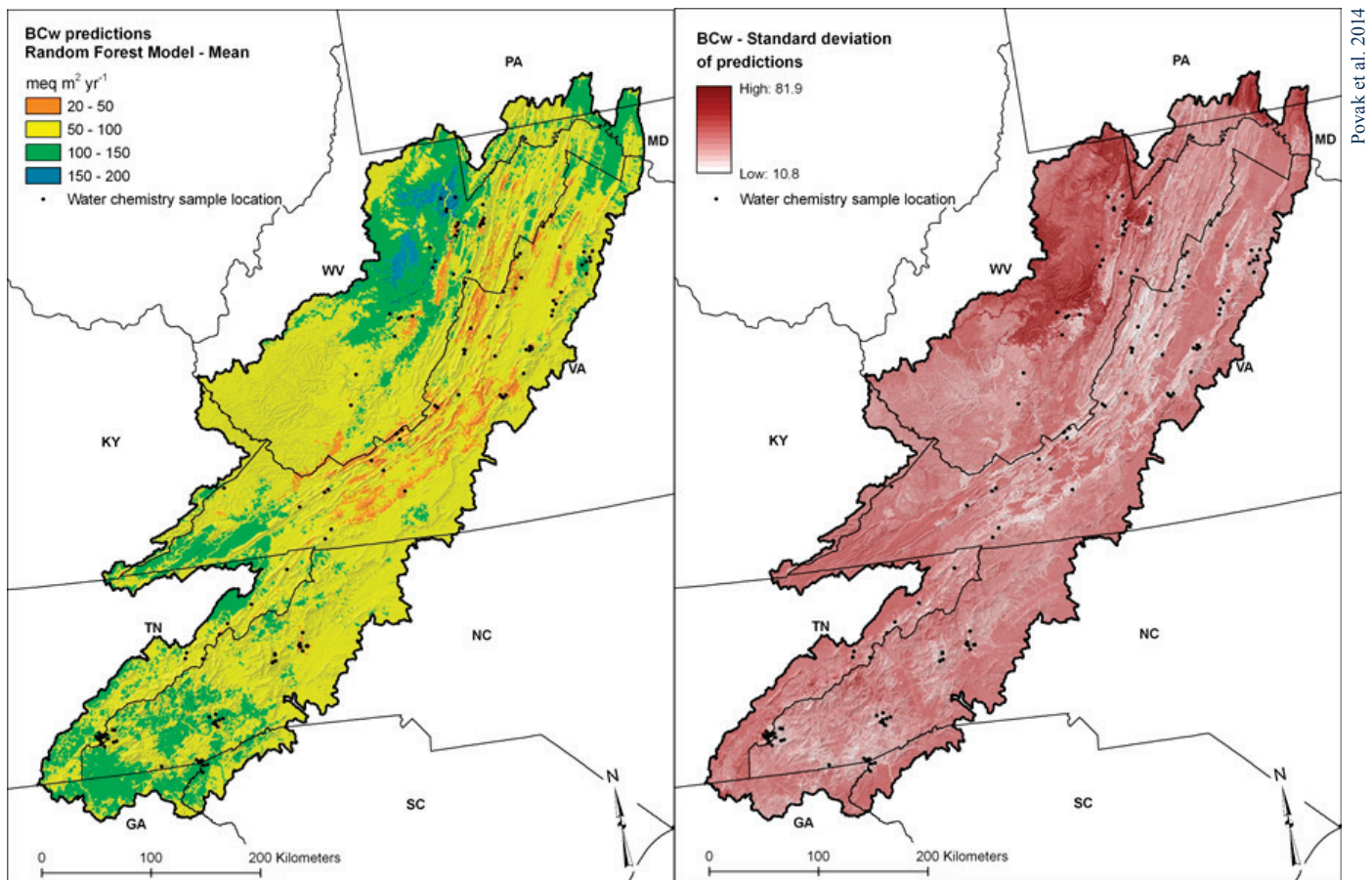
The figure on the left shows a continuous surface of predicted base cation weathering (BC_w) rates. Orange marks areas with the lowest BC_w rates; these are the most vulnerable to sulfur deposition and acidification. High-elevation areas (above 2,500 feet) are vulnerable to sulfur deposition because these are frequently exposed to acidic clouds. Soils in these areas are insufficient to buffer sulfuric acid inputs. The figure on the right shows the standard deviation of predictions from the final model. Areas in darker red show higher uncertainty of BC_w predictions.

MODELS HELPING MODELS

"The base cation weathering prediction was just the middle of a continuum," Reynolds says. The model they developed for predicting BC_w rates was used alongside another model they developed that predicted stream water acid-neutralizing capacity to then estimate critical loads of acidic sulfur deposition. These critical load estimates were then used within a customized decision support tool, designed by the researchers and their collaborators.

"The decision support tool does a strategic evaluation of the landscape," Reynolds says. "The predictions of critical loads, BC_w, and stream water acidity were used to make predictions about potential biological impacts on fish and aquatic insects. The modeling to improve BC_w predictions was fundamental to that entire process." Reynolds continues, "The complete tool can help resource managers assess the effects of increased sulfur deposition on native and nonnative fish and aquatic invertebrates within the watersheds."

National forest managers and EPA regulators in the study region are already using the tool to plan and conduct mitigation measures for acidified watersheds and streams. Bill Jackson is an air resource management specialist for the Southern Region (Region 8) of the National Forest System, which includes the southern Appalachian Mountains. Jackson says, not only does the tool help him identify areas that may be at risk, it helps him estimate the risk caused by certain management events, like tree harvesting. "If we harvest trees in high-risk areas, what will that do?" Jackson

says. "Removing trees also removes base cations from the watershed." The results from the tool also alert him to areas where more data are needed. "If we want to manage a region that is at risk, the tool points us to specific areas to collect more soil information and water chemistry."

Jackson notes that sulfur deposition has actually dropped rapidly in the eastern United States over the past several years. He says regulations put in place by the Clean Air Act have helped immensely. "We want to account for those improvements," he says. "I updated the model with recent sulfur deposition estimates and supply them to the model. I like that about this tool—that we can update or modify all of the essential inputs."

Hessburg says the tool can be readily adapted to other regions where resource managers need accurate critical load estimates over large areas. "One of the most exciting things to us is that we had a highly functional, cross-disciplinary interaction that enabled us all to build a useful tool, and now managers are using it throughout the southeastern national forests to evaluate their management options, and make further policy decisions," Hessburg says. "It's science that's having an impact."

"Look deep into nature, and then you will understand everything better."
—Albert Einstein

LAND MANAGEMENT IMPLICATIONS

- Model results significantly refine prior base cation weathering rate estimates and can be used in policy discussions on pollution sources, air and water quality regulation, and water quality mitigation associated with acidified streams.

- The model has been used along with predicted stream water acid neutralizing capacity to identify watersheds where sulfur deposition levels will likely lead to long-term detrimental effects on aquatic organisms. This information has been incorporated into a forest plan assessment and an environmental assessment for proposed land management actions.

- Results are being used in a customized decision support tool to assess the consequences of increased acidification on native and nonnative fish and aquatic invertebrates within study area watersheds.

- National forest managers and Environmental Protection Agency regulators in the study region have used the critical load and biotic impact predictions to monitor aquatic habitat and plan mitigation for acidified watersheds and streams.

FOR FURTHER READING

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