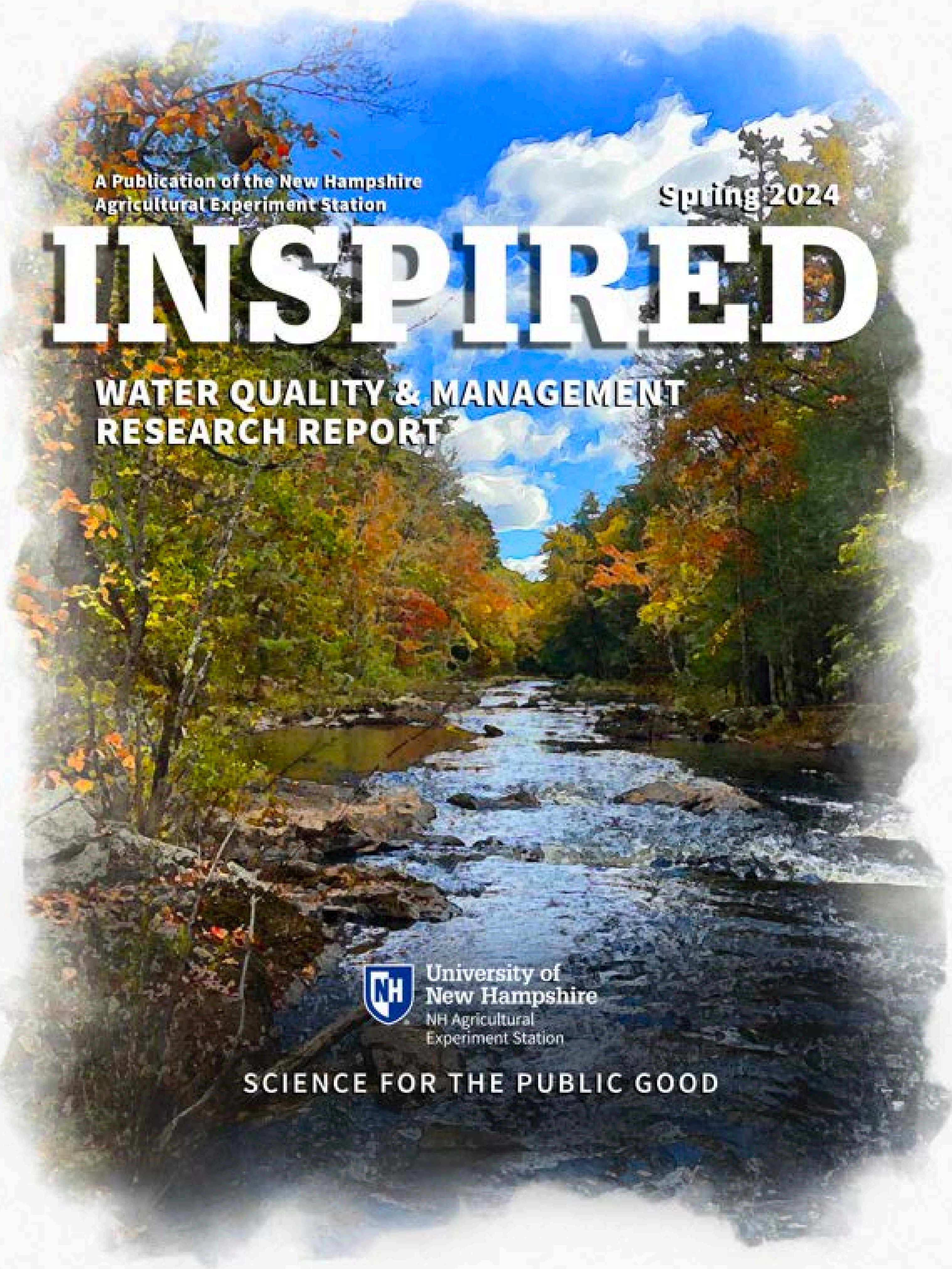


A Publication of the New Hampshire Agricultural Experiment Station

Spring 2024

INSPIRED

WATER QUALITY & MANAGEMENT RESEARCH REPORT

University of New Hampshire
NH Agricultural Experiment Station

SCIENCE FOR THE PUBLIC GOOD

MESSAGE FROM **THE DIRECTOR**

Dear members of the New Hampshire conservation community and beyond:

For over a century, the New Hampshire Agricultural Experiment Station has recognized the diverse importance of rivers, streams, ponds and lakes to the many communities of our state. They provide the water we drink, sustain our food systems, contribute to the infrastructure and economies that strengthen our communities, add beauty to our landscapes and support the many ecosystems we share. In turn, it is our responsibility to leverage our knowledge and science-informed practices to manage this resource for current and future generations of Granite Staters.

The research described in this issue provides findings and perspectives about how innovation and discovery is used to protect water quality, remediate pollution and better understand the impacts on and of climate change. The briefs help inform about the effects of urbanization on water chemistry and the roles of plants, bacteria and their interactions on reducing the adverse effects of harsh chemicals entering waterways; the manner in which cost-effective adaptation to existing sensors and the use of increasingly available unmanned aerial systems can increase both the accuracy of measuring water quality and the safety of those tasked with making measurements; and, the roles that rivers play in capturing carbon and methane from entering the atmosphere and how changing weather patterns may be impacting those climatic contributions.

Each research brief offers a perspective about the rigorous science and impactful takeaways that can be implemented by landowners, agencies and non-profit organizations and policy makers to make informed, tested decisions for managing our water resources. Ultimately, the science that supports effective management of the most important public good is critical to ensuring the sustainability and resilience of New Hampshire.

Thank you for supporting our efforts to improve the lives of every Granite Stater.

ANTON BEKKERMAN
Director, NH Agricultural
Experiment Station

INSPIRED CONTENT

SCIENCE FOR THE PUBLIC

LOCALLY INSPIRED. GLOBALLY IMPORTANT.

High-Stakes Issues
World-Class Science
Sustainable Advancement

The mission of your New Hampshire Agricultural Experiment Station (NHAES) is to ensure the resiliency of the Granite State's diverse communities and local economies. For more than 130 years, we've served the state as the agricultural, food, natural resource and environmental research arm of the UNH land-grant mission. From the lab to the field, forest and sea, our researchers push scientific frontiers in pursuing sustainable food production and natural resource management across New Hampshire and beyond.

New Hampshire is a state powered and supported by its freshwater bodies—from hydroelectric dams that harness river currents to rivers that provide food, support regional ecosystems, and drive local recreation, tourism and economies. The Granite State has more than 800 lakes and ponds and approximately 19,000 miles of rivers and streams, adding over $200 million from recreational fishing, attracting nearly half a million visitors to enjoy the state's freshwater swimming

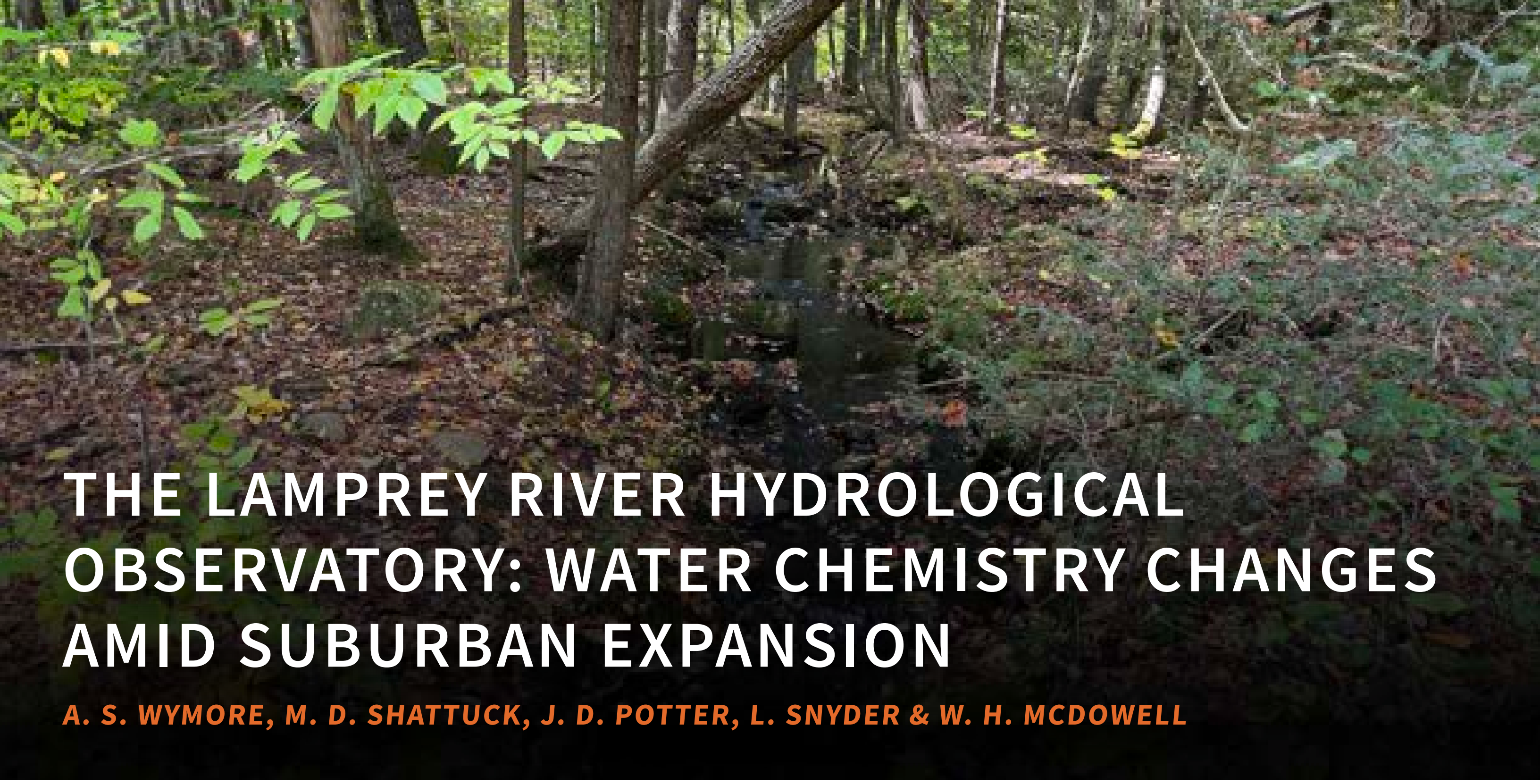
Duckweed plants growing in surface water (left); a researcher collects water samples in Durham, NH (center); and a river in southeastern New Hampshire following a major precipitation event (right).

GOOD

and surrounding communities, and providing ecosystem services that ensure a clean drinking water supply, run-off water filtration, erosion management, resilient wildlife habitats and flood mitigation.

As a changing climate, increasing urbanization and evolving policies continue to impact our state's natural water systems, the importance of science-based, measured and forward-looking approaches to keeping our state's waters managed for long-term sustainability is a core mission of the NHAES. Researchers with the NHAES are helping to lead the advancement of methods to accurately assess how waters in the Granite State are affected and to develop cost-effective management and policy solutions.

By testing new and emerging technologies, studying and adapting lessons from within New Hampshire and from far outside and leveraging insights from an increasing amount of and breadth of data, the discoveries from Station scientists are rapidly enhancing our understanding of how one of our state's most prized environmental and economic resources can remain resilient even in the face of an uncertain climate and future.



THE LAMPREY RIVER HYDROLOGICAL OBSERVATORY: WATER CHEMISTRY CHANGES AMID SUBURBAN EXPANSION

A. S. WYMORE, M. D. SHATTUCK, J. D. POTTER, L. SNYDER & W. H. MCDOWELL

From its headwaters near Northwood Meadows State Park in Northwood, NH, the Lamprey River meanders for more than 50 miles until it empties out into New Hampshire's Great Bay estuary. Like many rivers in the state, the Lamprey River—and nearly a dozen tributaries that empty into the Lamprey River—moves through forested regions and agricultural lands as well as through municipal downtowns and a variety of mixed-use and suburban landscapes. This diversity of landscapes enables the opportunity to assess how changes in land use and land cover impact water quality over time. Data describing Lamprey River's water quality for more than 20 years can show the impacts of climate change, suburbanization and mixed land-use environments on water chemistry and nutrient export to the Great Bay estuary.

KEY TAKEAWAYS

Monitoring data from more than 20 years indicate rising nitrate levels and changing water chemistry in the Lamprey River watershed in New Hampshire, likely linked to increased suburbanization.

River dynamics reflected climate shifts, with more rain, less snow and altered seasonality occurring over the last two decades.

Cleaner precipitation but increased nitrogen pollution are impacting downstream estuarine health of New Hampshire's Great Bay.

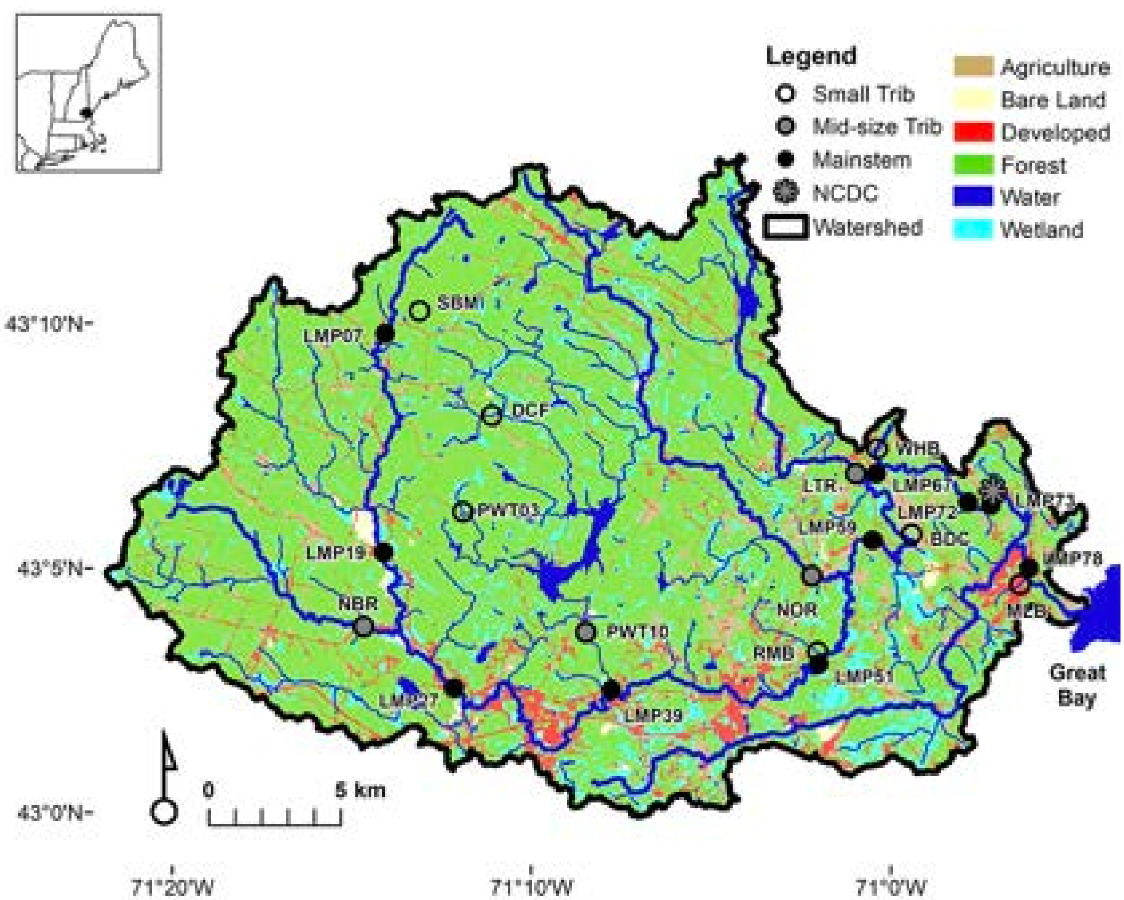
Background and Key Concepts

The Lamprey River Hydrological Observatory (LRHO) has collected more than 20 years of data describing the chemistry and hydrology of the 212-square-mile Lamprey River watershed, providing a baseline of data on river and stream discharge, levels of nitrogen and greenhouse gases (including methane and nitrous oxide) and dissolved organic matter. These data offer a historic look at how a developing landscape and warming climate have affected the watershed as well as a comparison of future climate change-based measurements. As a result, the data set can be used to identify different trends, such as quantifying how a loss of forest cover—due largely to suburban development—has resulted in increased levels of nitrate found in the Lamprey River's tributaries, which span a range of forest cover levels (**Fig. 1**).

Long-term research of the Lamprey River can provide particularly impactful insights. Its partial protection under the National Wild and Scenic Rivers Act and passage through areas growing in population density—where most households use on-site waste disposal, such as septic systems, that can pass nitrogen into water runoff—offer conditions for studying the impact of suburbanization on a major water body. The river's location in a temperate region, where winters are experiencing less snow and more rain than they did two decades ago and the transitional seasons between winter (spring and fall) are lengthening, make it an ideal watershed for studying climate change impacts.

The study's length also allows sufficient data to characterize river dynamics following extreme weather events, including multiple record-breaking winter and summer droughts; consecutive 100-year-scale floods (in 2006 and 2007); and shifting seasonal changes such as shorter winters and longer springs. Additionally, the analyses can identify changes in the chemistry of surface water within the watershed over time, such as determining the extent to which nitrate levels within the river and tributaries are slowly rising while dissolved organic nitrogen is steadily decreasing. However, how this will impact downstream waterbodies, like the Great Bay estuary, remains largely unknown.

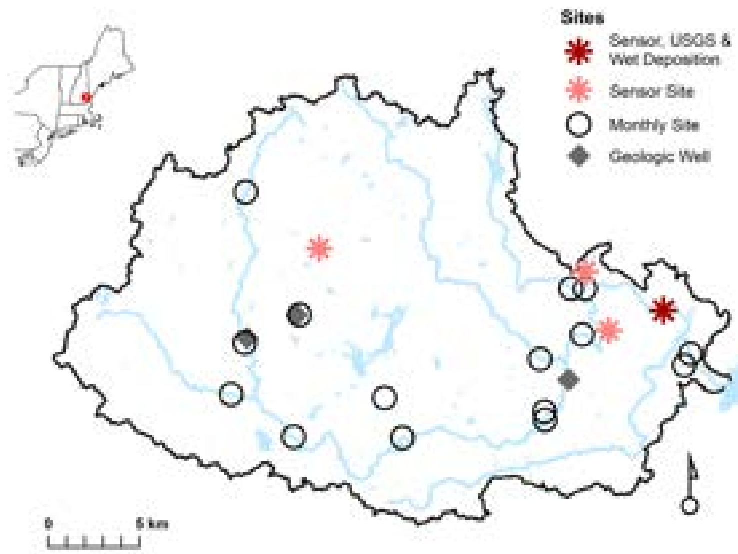
Figure 1. Map of the Lamprey River Hydrological Observatory in southeastern New Hampshire. Land use data from NOAA Coastal Change Analysis Program (2016). NCDC, National Climate Data Center.



Methodology

Traditional water sampling has occurred since 1999, with samples being collected from over 20 sites weekly or monthly (**Fig. 2**). In 2013, a series of high frequency remote sensors were installed throughout the watershed to provide continuous data on water nutrient levels. Sending data transmissions every 15 minutes, these sensors collected data throughout New Hampshire winters, whereas similar water quality studies in similar climates often remove their sensors during the winter months. Additionally, because of their multi-probe design, these sensors can collect an array of statistics, including nitrate and dissolved organic matter concentration, pH levels and temperature, dissolved oxygen, turbidity, and more. This offers a more complete, real-time characterization of conditions in the rivers and streams.

Figure 2. Stream sampling locations within the Lamprey River Hydrological Observatory of the Lamprey River watershed.



Note: Sensor sites indicate high-frequency sensors that test water quality every 15 minutes. Grab samples are conducted at monthly sites, as well as sensor sites (every 2-4 weeks). Geologic wells refer to drilled monitoring sites used to monitoring water levels and quater quality (conducted in collaboration with the NH Geological Survey.

The dual monitoring approach enabled creating a detailed and dynamic picture of the Lamprey River over an extensive period. The weekly samples offered a longitudinal dataset, allowing for the tracking of changes and trends that might otherwise be lost in less frequent sampling. The high-frequency sensor data provided the granularity necessary to understand the river's responses to short-term events and seasonal variations.

These data were also used to examine fluxes of greenhouse gases—including methane and nitrous oxide—thereby contributing to an understanding of the watershed's role in broader climate patterns. Additionally, the nested-watershed design facilitated an analysis of the spatial variability across the watershed, ensuring a thorough understanding of the different forces at play in the various sub-environments within the river system.

Results and Impacts

The data from the Lamprey River show clear signs of the surrounding area's suburban growth affecting water quality. Higher levels of nitrate have been consistently recorded, suggesting that as the region develops, the water quality is changing. This trend is concerning because nitrate can be harmful to aquatic ecosystems and human health. At the same time, there's been a notable decrease in dissolved organic nitrogen, which could affect the river's natural processes.

Furthermore, the climate patterns around the Lamprey River are shifting. Winters have become shorter and springs longer and the region is experiencing more extreme weather, including severe droughts and floods. These conditions stress the river system and can lead to longer-term impacts on water quality.

Implications for the Future

This study points to a need for strategies that can handle the likely effects of higher residential density and changing weather and climate patterns. Furthermore, the health of the Great Bay estuary, which the Lamprey River is the largest river contributor to by water volume, depends on understanding and managing these changes effectively. This ongoing research provides important checkpoints that can help us see how human activities and climate patterns affect the Lamprey River, and this understanding is crucial for making informed decisions about managing watersheds, freshwater resources and the environment more broadly.

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PLANT RESPONSES TO AN URBANIZATION CONTAMINANT

A. O'BRIEN, J. LAURICH & M. FREDERICKSON

A plant's traits can vary due to its genetics and due to experiences during that organism's life, which can result in different traits. Experiences that can change the influence of genetics on traits include changing interactions with other organisms, or environmental context. Urban environments are very different from rural environments, and could be one such context that shifts plant traits. For aquatic plants, urbanization could be particularly influential due to a higher density of pollutants in water ways, and how specific contaminants impact plant evolution and traits is an area of research need.

KEY TAKEAWAYS

Levels of heavy metal contaminants in water differ across urban and rural environments, and these differences can have complex impacts on the ecology and evolution of aquatic plant organisms.

Duckweed, a model aquatic plant, would be minimally affected by the common pollutant zinc – if it weren't for the effects of zinc that act through the microbiome.

Zinc exposure at levels commonly found in urban environments disrupted interactions between duckweeds and their local microbiomes, significantly worsening plant and microbial growth.

Duckweed as a Model Aquatic Plant

Aquatic environments are especially impacted within urban landscapes, where there are water bodies contaminated with pollutants from human-built surfaces. A particular contaminant is the heavy-metal zinc, originating from roofs, tires and metal structures. To begin understanding aquatic plants' plasticity—

experiences during an organism's life that can result in the development of different traits—and genetic trait variations, the research assessed populations of a model aquatic plant duckweed (*Lemna minor*) across an urban-to-rural gradient. Specifically, the goal was to quantify the extent to which duckweed traits depended on three components: the presence of zinc, the variation found in microbial communities collected across the urban-to-rural gradient and the variation across the duckweed genotypes themselves

Microcosms to Understand Sources of Trait Variation

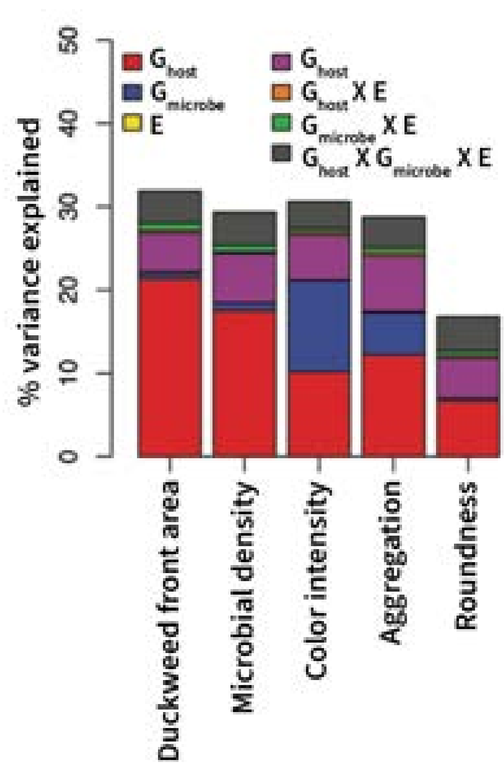
The study created small, experimental microcosms that are meant to mimic characteristics of larger environments. The microcosms contained duckweeds collected from across different urban, rural or intermediate environments, along with microbes collected from duckweeds at the same sites. Each microcosm was grown either without zinc or with the contaminant at levels found in highway runoff and in nature. The researchers factorially combined all possible combinations of the 10 sources of duckweeds and microbes (100 combinations in total) in both contaminated and uncontaminated microcosms, with each well in a well plate representing a unique microcosm (**Fig. 1**). After letting the microcosms grow, plant growth and traits of each microcosm were assessed, including total microbial cell density.

Example of duckweed microcosms in a well plate. Each well contains different environmental characteristics.

Results and Impacts

Scientists have long known that variation in plant genomes contributes substantially to variation in plant traits. However, aspects of plant abiotic factors such as pollution or biotic factors like microbiomes can also contribute to plant traits.

Figure 1. Percent of variation explained by treatments for duckweed fitness (frond area), and each trait, including total microbial density (optical density at 600 nm, a measure of summed microbial growth across community members).



For duckweed, the study found that differences in microbes from across the sites where duckweed grew contributed nearly as much to variation in plant traits as did variation in plant genomes—especially when considering the genotype-dependent effects of microbiomes. Specifically, plant genomes contributed up to 21% across traits, microbiomes up to 11% alone, but up to 16% including plant-genotype dependent effects. In contrast, pollution and the effects of pollution that depended on microbiomes contributed very little to differences in plant traits.

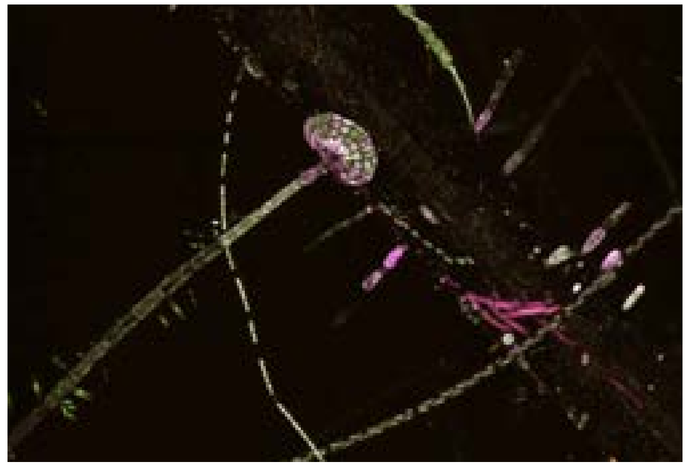
Genotypes of plants sourced from urban environments grew faster, which matches similar observations of other organisms from urban environments. Otherwise, the traits of the duckweed genotypes from urban and rural environments did not consistently differ.

Communities of microbes from urban and rural environments did not have consistently different effects on duckweed traits. However, this depended on the presence of zinc, which disrupted interactions between duckweeds and their microbiomes when at a level commonly found in urban environments. In the presence of a zinc contaminant, combining microbiomes and duckweeds collected from the same site resulted in reduced plant and microbial growth. Interestingly, other researchers have also found that urban environments can disrupt interactions between plants and their microbes.

The researchers also found that microbiome composition predicted effects on plant traits, regardless of the zinc treatment. Microbiomes that were very similar in composition had very similar effects on duckweed traits (**Fig. 2**).

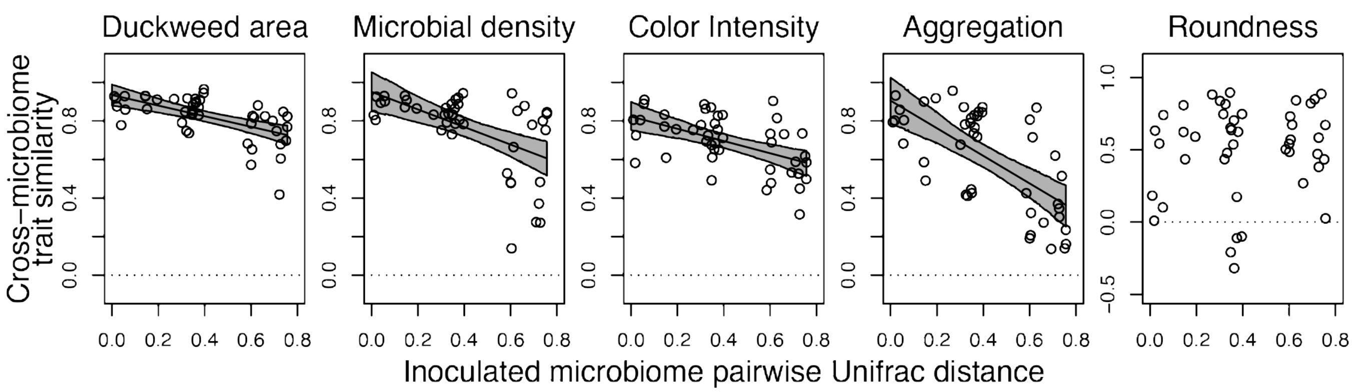
Implications for the Future

The research found that the urban contaminant zinc did not directly impact aquatic plant traits. However, there were many indirect effects of zinc on duckweed growth and traits via microbiome-dependent effects, shifts in evolutionary pressures and shifts in trait heritability. Future research should consider how indirect ecological, evolutionary or combined effects of contaminants entering waterways might impact aquatic life. Moreover, municipal, state and regional communities should be aware of the complex manner in which water contaminants can impact local aquatic plant life.



Microscopic image of duckweed organism. Image credit: Nicholas Deakin and Anna O'Brien.

Figure 2. Similarity of trait values of duckweeds (y-axis) is higher when the dissimilarity of the microbiomes across which they are compared is lower (x-axis).



Note: Plots from left to right represent different fitness and trait measures: duckweed frond area (duckweed fitness), microbial density (optical density at 600 nm, a measure of total microbial growth), duckweed frond color intensity, duckweed area:perimeter ratio (aggregation), and duckweed frond roundness. Lines and shaded regions represent predicted mean and 95% highest posterior density intervals (HDPIs) for significant relationships. Each point's pairwise trait similarity (y-axis value) is a correlation between duckweed genotype means across one pair of inoculated microbiomes.

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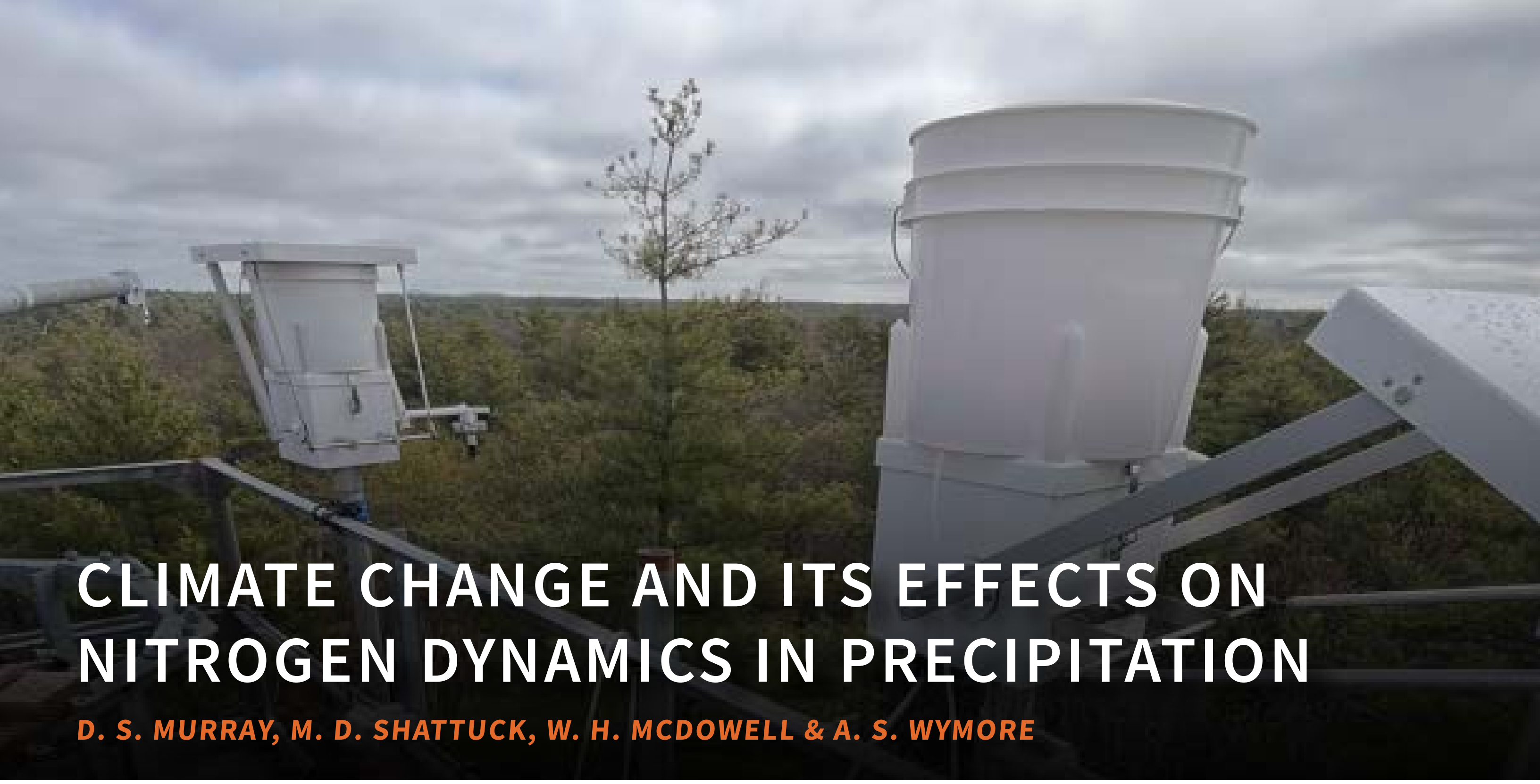


CLIMATE CHANGE AND ITS EFFECTS ON NITROGEN DYNAMICS IN PRECIPITATION

D. S. MURRAY, M. D. SHATTUCK, W. H. MCDOWELL & A. S. WYMORE

New Hampshire and northern New England experienced significant land cover changes from forest to farmland and back again over the past century, and surrounding ecosystems have served as early indicators of environmental sensitivity to the impacts of these land cover changes. For example, acid rain was first identified in North America at New Hampshire's Hubbard Brook Experimental Forest. As lands once used for agriculture have reverted to second-growth forests, they play a crucial role in the nitrogen cycle by absorbing atmospheric nitrogen deposits. However, as the northeastern United States grapples with elevated levels of nitrogen largely from food imports and atmospheric deposition, the ecological consequences are becoming more apparent, including alterations to forest nitrogen cycles and eutrophication in coastal waters.

KEY TAKEAWAYS

Total dissolved nitrogen in precipitation has decreased, with a notable reduction in ammonium and nitrate and an increase in dissolved organic nitrogen.

Nitrate is found in higher concentrations in snow, whereas rain is more enriched with ammonium.

Warming winters and shifting seasonality could alter the chemistry of the precipitation, impacting regional biogeochemical cycles.

Nitrogen Deposition

Nitrogen deposition not only influences plant growth and carbon sequestration but also affects the acidification of surface waters and the overall biodiversity within forest ecosystems. Despite efforts to manage nitrogen pollution, the region still faces the challenges of balancing agricultural productivity and energy demands with the need to protect ecosystem health and environmental integrity. This backdrop sets the stage for understanding the nuanced shifts in nitrogen deposition documented in recent studies and emphasizes the need for regional insights into these changes and their broader ecological impacts.

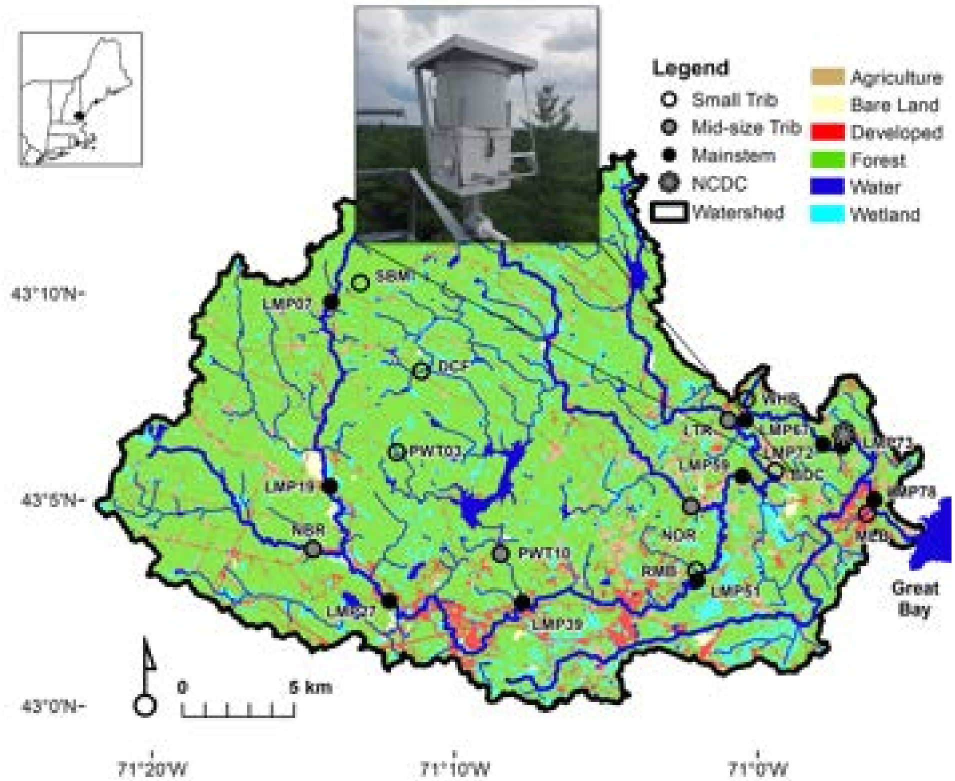


Figure 1. Land-use map for the Lamprey River watershed and the location of the wet deposition collector on UNH's Thompson Farm (TF). NCDC, National Climate Data Center.

Methodology

This study leveraged 17 years of data, making it one of the longest-running studies of organic nitrogen precipitation in the world. Data were gathered from a wet deposition collector located at UNH's Thompson Farm in Durham, NH, situated within New Hampshire's Lamprey River watershed (**Fig. 1**).

The timespan of this study offers insight into how the various forms of nitrogen deposited by rain and snow have changed over time and how nitrogen levels and types are connected to precipitation and human impacts on the environment, including climate change.

While national trends indicate a decrease in inorganic forms of nitrate deposited by precipitation, regionally there has been an uptick in organic nitrogen levels. These shifts can be tied back to both human activity and a changing climate.

The study focused on three forms of nitrogen: nitrate, ammonium and dissolved organic nitrogen. It then looked at the relationship between these forms of nitrogen and how they changed seasonally and with the type of precipitation deposited, whether it was falling as rain or snow.

Results and Impacts

The data indicate that total dissolved nitrogen from wet deposition is declining. However, the type of nitrogen present is changing, with both ammonium and nitrate decreasing and organic nitrogen increasing. And as organic nitrogen becomes a larger part of the nitrogen mix, the implications for ecosystems could be significant. For example, organic nitrogen often needs to be converted by soil microbes into forms that plants can use, which can slow plant growth, especially in ecosystems with more balanced nitrogen forms. This process can affect the timing of nutrient availability in surface water and the overall nutrient cycle.

In water bodies, increased organic nitrogen can contribute to issues like harmful algal blooms, which degrade water quality by consuming oxygen and releasing toxins, thus affecting aquatic life and making the water unsafe for drinking and recreation. Understanding these shifts is crucial as they play into the larger puzzle of ecosystem health, influencing everything from the diversity of plant life to the integrity of aquatic habitats.

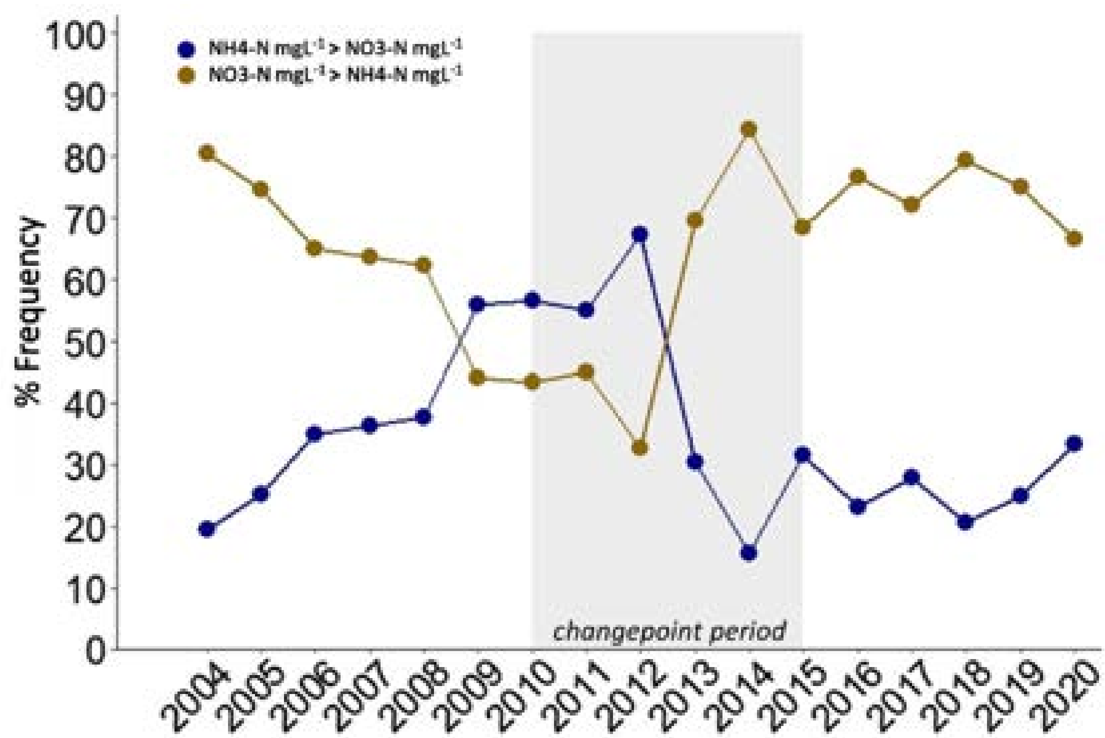
The type of precipitation also influences the nitrogen mix. Snow seems to have more nitrate compared to rain, which carries more ammonium. This is due to differences in the surface area between snow and rain and their ability to scavenge particles in the atmosphere. But as the climate changes and winters become warmer, it is possible to see more rain and less snow, implying more of nitrogen coming down could be in the form of ammonium-rich rain.

A shift toward more ammonium-rich rain due to warmer winters has unique implications. For one, ammonium can be directly used by plants, potentially altering growth patterns and competitive balances within plant communities. However, if the ecosystem's capacity to utilize this ammonium is exceeded, it can lead to leaching into waterways, contributing to eutrophication—a process where excess nutrients foster overgrowth of algae that depletes oxygen and harms aquatic life. This change in nutrient dynamics can ripple through the food web, affecting not just the local watershed but also the coastal areas that are connected to it, as excess nutrients are carried downstream, potentially leading to hypoxic zones where aquatic life struggles to survive.

Implications for the Future

This study shows how even the invisible elements like nitrogen in precipitation are changing. Understanding these patterns is crucial for predicting and managing the health of ecosystems, like that of New Hampshire's Lamprey River watershed. This knowledge can help communities and policy makers make more informed decisions when preparing for potential future environmental challenges.

Figure 2. Frequency (%) of deposition samples in a given calendar year where NO_3^- (nitrate) concentrations exceeded NH_4^+ (*in brown*), and where concentrations of NH_4^+ (ammonia) exceeded NO_3^- (*in blue*) within the Lamprey River Hydrological Observatory.



Note: The shaded region in panel represents the range of years with significant changepoints. The measurement mgL^{-1} is one milligram (dissolved) per one liter of water.

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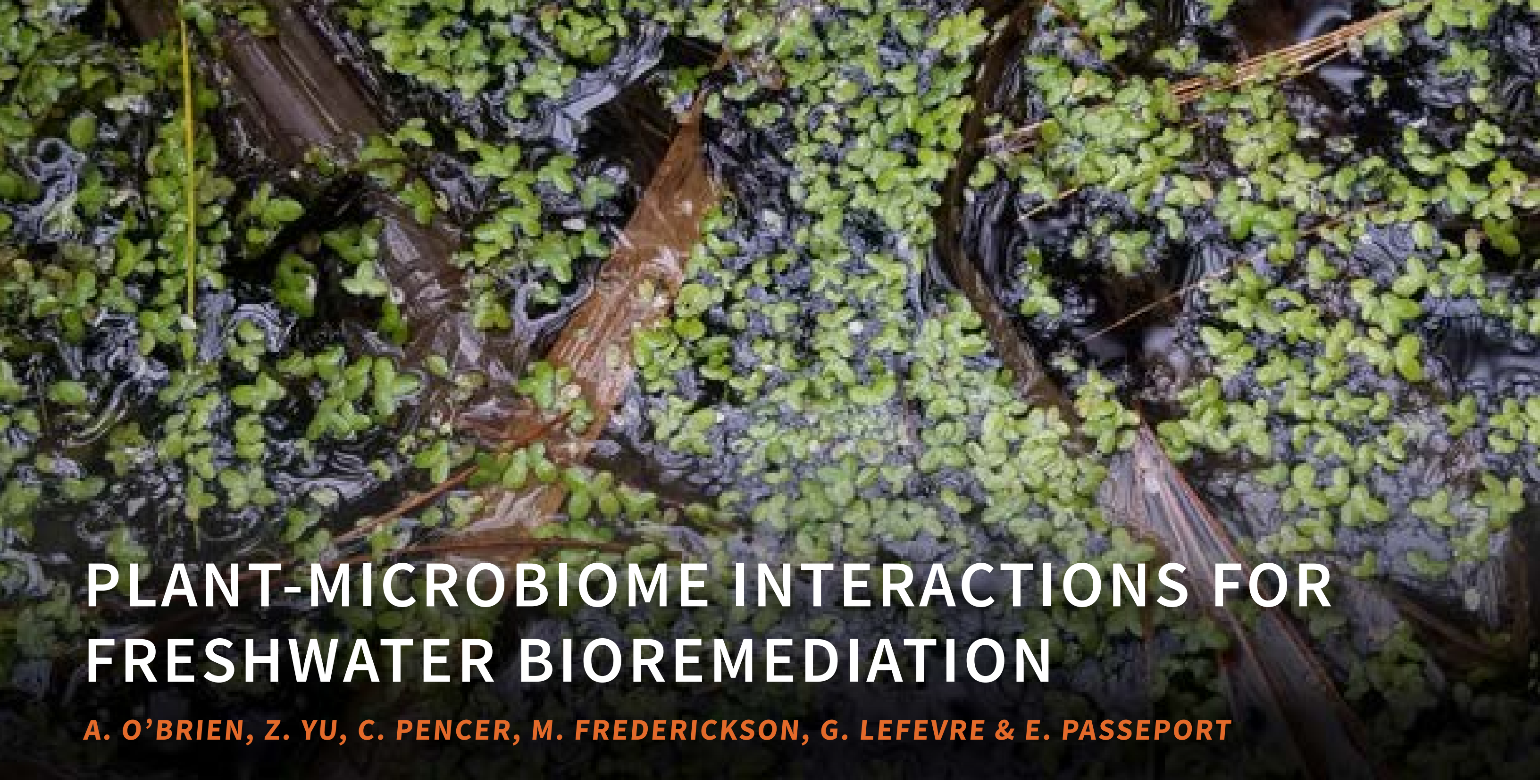


PLANT-MICROBIOME INTERACTIONS FOR FRESHWATER BIOREMEDIATION

A. O'BRIEN, Z. YU, C. PENCER, M. FREDERICKSON, G. LEFEVRE & E. PASSEPORT

As urbanization and the expansion of urban areas increase, there is greater importance to managing urban ecological issues such as increased contaminants in stormwater. In the northeastern United States, heavy reliance on road salt and use of anti-corrosive compounds such as benzotriazole continues to impact freshwater lakes and threaten aquatic life because these compounds can remain in water for long periods. While reducing the use of these compounds is necessary, it is also important to understand whether bioremediation is possible to lower existing concentration levels in freshwater lakes.

KEY TAKEAWAYS

Harnessing variation in plants and microbiomes could impact and improve bioremediation—the process in which biological systems transform organic contaminants into less toxic byproducts.

Experimental microcosms showed that duckweeds rapidly transformed and bioremediated the organic contaminant benzotriazole—a chemical used in industrial, commercial and consumer products.

Background and Key Concepts

Natural and constructed wetlands are key tools for managing urban stormwater, largely because plants and microbes will transform many organic pollutants into less dangerous products. However, constructed wetlands vary in effectiveness, suggesting that we have opportunities to improve effectiveness. One potential source of improvement could be leveraging diverse microbial communities—microbiomes—to help transform contaminants. Testing this and assessing the benefits of this approach could help inform water management strategies.

Methodology

More than 2,500 constructed microcosms—small, experimental microcosms that are meant to mimic characteristics of larger environments—were used to demonstrate how naturally occurring and manipulable biological variation could be harnessed for water bioremediation in a model plant-microbiome-contaminant system: the common freshwater plant duckweed (*Lemna minor*). Duckweed genotypes from 50 sites were matched either with their co-occurring microbiomes or had their microbiomes disrupted, and each of these 100 combinations was crossed with six different contaminant mixes of the winter co-contaminants benzotriazole and salt (sodium chloride) in microcosms. Further treatments also manipulated a single-celled green microalgae, *Chlorella vulgaris*.

Microcosms were developed in small scale well-plates (**Fig. 1**). These 2,500 microcosms fit in the footprint of a single shelf in a single growth chamber. Imagery was used to evaluate duckweed growth in the microcosms, and mass spectrometry helped evaluate the concentration of 10 different known potential products of benzotriazole transformation.

Results and Impacts

In all experimental microcosms containing duckweed, there was evidence of rapid transformation of benzotriazole. The expected outcome was that high levels of salt would interfere with biotransformation of organic contaminants, but benzotriazole was rapidly transformed even in concentrations of salt at urban runoff levels.

However, not all duckweeds and microbiomes were expected to be equivalent if included in newly constructed wetlands. Duckweeds from rural sites, duckweeds with the added algae (*Chlorella vulgaris*), and duckweeds with diverse microbiomes could help optimize benzotriazole removal and minimize byproduct toxicity (**Fig. 2**).

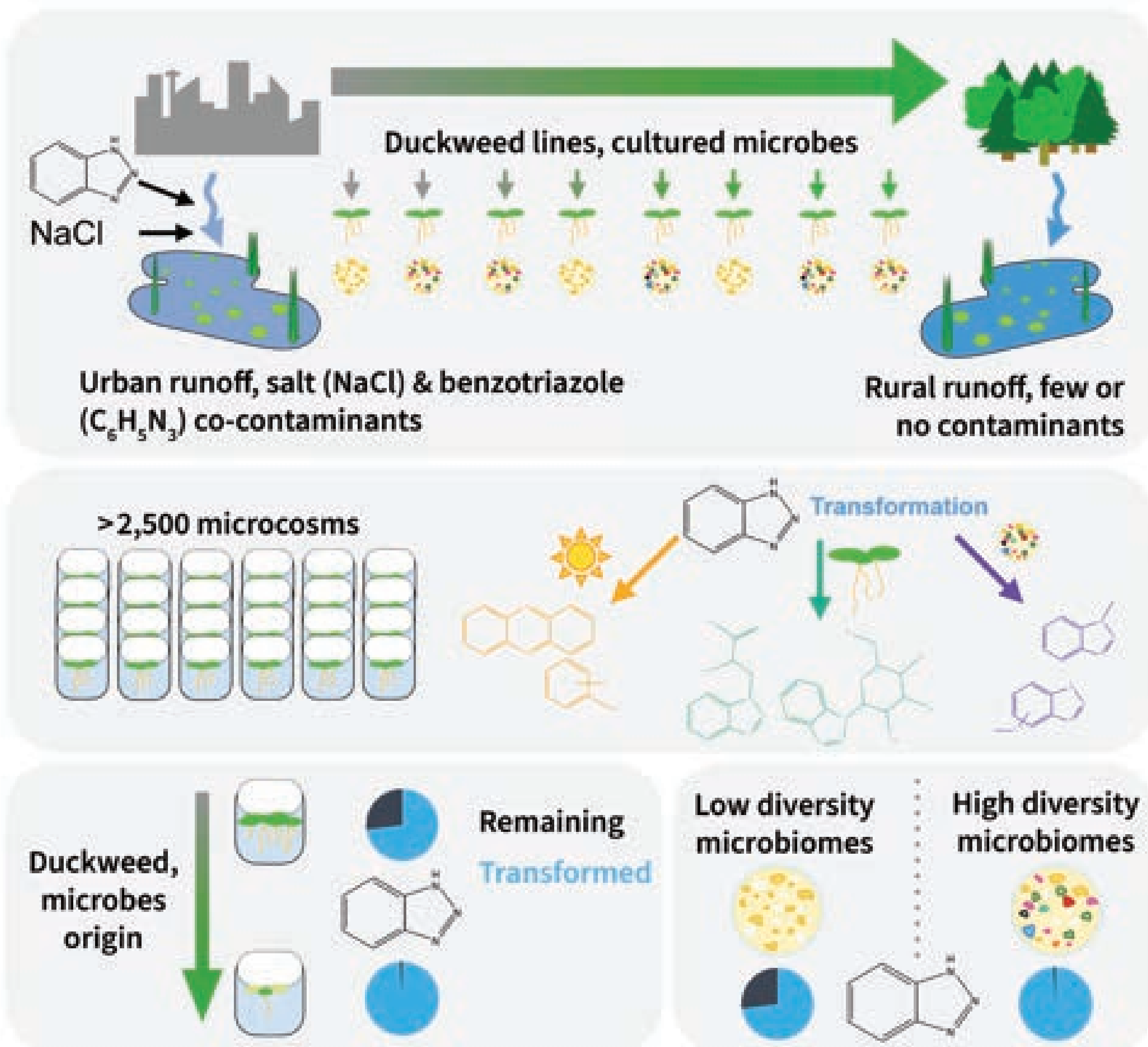
Greater growth of duckweed correlates with increased benzotriazole transformation, potentially through mechanisms like auxin, a plant growth-promoting hormone. This suggests that duckweeds might process benzotriazole as a pseudo-auxin and thereby receive analogous growth signals. Conversely, despite expectations, greater microbial density did not necessarily result in an increased production of transformation products.

The variability in microbial metabolism within diverse microbiomes may facilitate additional, yet

Figure 1. Example of duckweed, microbe, and contaminant microcosms from the experiment.

undetected, transformations of benzotriazole. Often, the full extent of these transformations remains unaccounted for, implying that more profound or complete mineralization processes could be occurring. However, without the presence of duckweed, microbial communities alone show limited capability in transforming benzotriazole. The organic carbon provided by duckweed is likely crucial for harnessing the metabolic diversity of these microbes, emphasizing the interdependence of host plants and their microbiomes in enhancing bioremediation efforts.

Figure 2. Relationship between the diversity of the naturally associated microbiome and the amount of benzotriazole removed across a subset of microcosms.



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THE ENHANCED POLLUTION FILTRATION ABILITIES OF LARGE WATERSHEDS

W. M. WOLLHEIM, T. K. HARMS, A. K. ROBISON, L. E. KOENIG, A. M. HELTON, C. SONG, W. B. BOWDEN & J. C. FINLAY

Akin to the circulatory systems within humans, river networks serve as vital conduits for our planet's wellbeing. Just as veins and arteries work with organs to filter out impurities, these waterways remove pollutants from diverse sources before reaching potentially more fragile downstream ecosystems. However, not all river networks perform this task with equal efficiency. This study sheds light on a remarkable phenomenon: as the size of a watershed increases, its ability to filter pollution escalates exponentially, a process termed 'superlinear scaling.' The research has important implications for New England—a region characterized by its variety of watershed sizes from small coastal watersheds to the large regional Merrimack and Connecticut river watersheds. Findings from this study can be used to support land-use strategies, which are crucial in maintaining local ecosystem balance.

KEY TAKEAWAYS

Watershed size significantly impacts a river network's pollution filtration ability, with larger watersheds showing a superlinear increase—an increase unproportionally greater compared to the increase in watershed size—in filtration efficiency.

Managing land use and mitigating non-point source pollution in smaller watersheds are priorities for protecting estuaries and oceans.

Results indicate that larger watersheds may release more carbon back to the atmosphere because of aquatic processes.

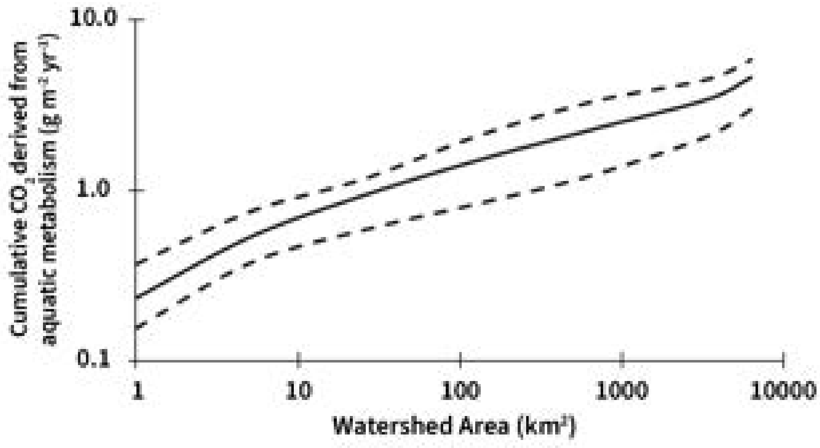
Methodology

The research used an innovative model to assess how different-sized watersheds process pollutants. This modeling integrated river network structure (shape), channel hydraulics (widths) and biogeochemical rates, and is analogous to aligning the metabolic process of an individual living organism to the entire system of those organisms based on a well-established set of factors. And while differences in biogeochemical functions of river networks may differ from those in portions of that network, these differences do not significantly alter the capacity to predict system-wide outcomes from the modeling.

Results and Impacts

The models' results indicate that larger watersheds with larger rivers are exponentially more efficient at filtering pollutants due to the intricate interplay among these characteristics.

Figure 1. Allometric scaling of net carbon production with increasing watershed area.



Note: Cumulative CO_2 derived from aquatic metabolism (cumulative ecosystem respiration (ER) – cumulative gross primary production (GPP), normalized to watershed area). Model results incorporate trends in the local rate of GPP and ER with watershed area for a rectangular river network at mean annual flow (500 mm yr^{-1}). Median (solid line), 25th percentile and 75th percentiles (dashed lines) are derived from 9 model scenarios that reflect potential variation in hydraulic dimensions.

The results show that pollution filtration does not increase linearly with watershed size but rather at a superlinear rate—disproportionally greater than the size of the watershed. This finding also suggests that carbon dioxide emissions from rivers in larger watersheds add relatively more to global emissions than smaller watersheds per unit of land (**Fig. 1**).

Additionally, the findings highlight the importance of managing smaller watersheds, as they are less equipped to naturally handle pollutants especially when there is a high rate of pollutant entry (high flow) into the river. The research also sheds light on rivers' roles in the global carbon cycle. Larger river watersheds have a disproportionately higher input into large scale cycling. However, this also implies that larger watersheds potential play similarly disproportionately larger roles in sequestering carbon.

Implications for the Future

This study is an important contribution to environmental policy and land-use management. With a new understanding of watershed dynamics, policymakers and public agencies can create more effective strategies to enhance water quality and address climate change impacts. The insights call for a recalibration of conservation efforts, particularly in New England where both nutrient pollution and carbon sequestration are factors, to leverage the natural filtration capabilities of river networks and better quantify their carbon release potential.

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ADAPTING AN OPEN-SOURCE CARBON DIOXIDE SENSOR FOR STREAMS AND RIVERS

A. K. ROBISON, L. E. KOENIG, J. D. POTTER, L. E. SNYDER, C. W. HUNT, W. H. MCDOWELL & W. M. WOLLHEIM

Rivers and streams play a pivotal role in the global carbon cycle, acting as significant sources of carbon dioxide (CO_2) emitters to the atmosphere. Recent technological advancements have enabled high-frequency monitoring of dissolved CO_2 in aquatic environments, particularly marine and freshwater bodies like lakes and ponds. However, due to their dynamic flow conditions in response to storms, moving freshwater ecosystems, such as rivers and streams, have proved difficult for measuring CO_2 accurately. This research assesses whether accurate high-frequency measurements can be achieved by adapting an affordable and existing CO_2 sensor to moving freshwater systems.

Methodology

This study adapted the SIPCO$_2$ high-frequency sensor for use in fast-moving and variable waters by adding features to enhance its durability and accuracy. Modifications included adding a mechanism allowing

KEY TAKEAWAYS

Water bodies significantly contribute to storing and releasing carbon dioxide (CO_2), impacting climate action planning.

Optimized CO_2 sensors (Lotic SIPCO$_2$) for use in flowing water ecosystems can accurately measure emissions, aiding in developing carbon budgets needed for effective climate change mitigation policies.

Sensor modifications enable real-time monitoring of CO_2 emissions from streams over daily cycles, during extreme weather events, and across seasons.

the sensor to rise and fall with flow conditions, a protective housing to withstand dynamic flow conditions and the use of materials that would resist microorganism damage. This approach allowed for more frequent and reliable CO_2 measurements, especially during extreme weather events that disrupt normal water flow patterns.

For this study, the adapted SIPCO$_2$ sensor was tested across 10 streams, covering a broad spectrum of land cover and basin sizes (**Fig. 1**). The modified design included mechanisms to prevent biofouling, adapt to fluctuating water levels and shorten the time needed for gas equilibration—the process used to calculate CO_2 levels (**Fig. 2**). By assessing the impact of various factors on the uncertainty of CO_2 emission estimates, the study highlights the importance of gas exchange velocity and sensor accuracy, especially when CO_2 levels are near the point at which the water has absorbed as much CO_2 as it can hold at a given temperature and pressure.

Results and Impacts

The adapted sensors demonstrated high reliability in measuring CO_2 levels across various streams

Figure 1. Map of 10 monitoring locations in streams and rivers in New Hampshire and Massachusetts.

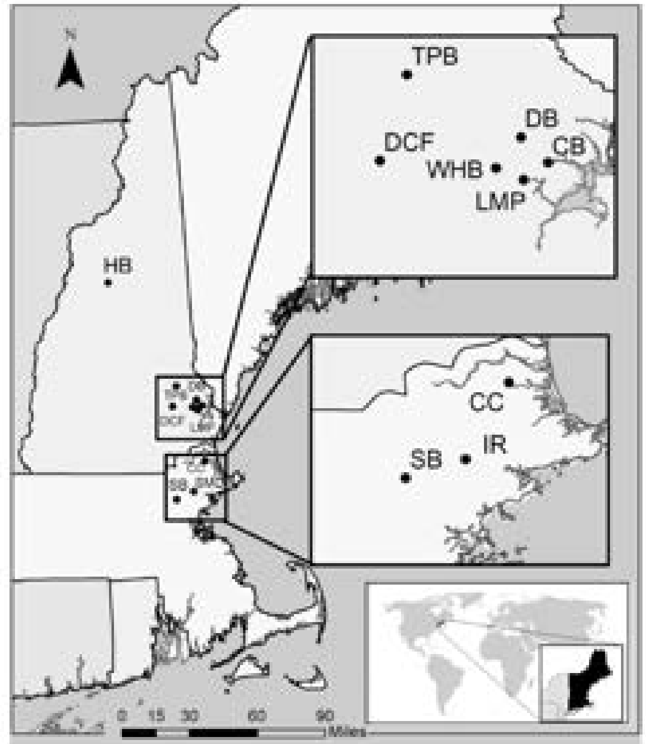
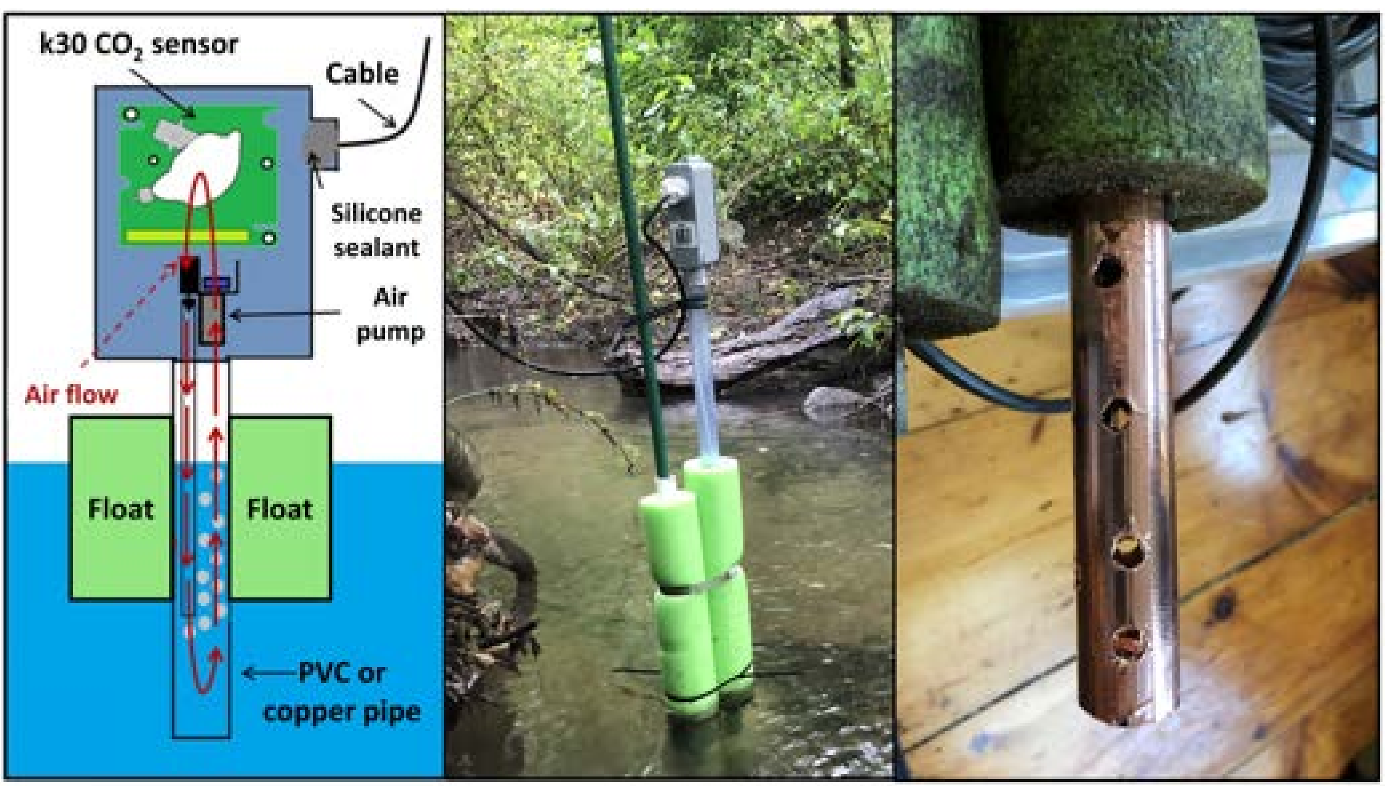


Figure 2. Left: The Lotic-SIPCO$_2$ sensor design, adapted from Hunt et al. (2017). Center: An example deployment of lotic-SIPCO$_2$ sensor with novel float design. Right: Image of the submerged portion of a lotic-SIPCO$_2$ sensor with copper tape coating to minimize biofouling.



and identifying significant differences in emission magnitudes (**Table 1**). The capability to monitor CO_2 fluctuations continuously provides valuable insights into how land use changes, such as deforestation or urban development, can impact carbon emissions. For example, this information can aid scientists in identifying how land use changes and land management practices correlate with increases or decreases in CO_2 emissions while also supporting the accuracy of climate modeling and informing policy decisions. Furthermore, the research sheds light on the underlying mechanisms driving these changes, such as alterations in stream metabolism and runoff dynamics.

Implications and Strategic Recommendations

The Lotic-SIPCO$_2$ system represents significant progress toward cost-effective and reliable method for tracking CO_2 concentrations and emissions across various stream and river environments, which has previously been achieved for lakes, ponds and marine ecosystems. Assessing the newly developed tool for measuring CO_2 emissions in moving freshwater environments offers several insights:

- Optimized CO_2 sensors can be used across New Hampshire's waterways to gather comprehensive data on carbon emissions and help inform state climate action plans.
- Higher-frequency sensors can produce data that help emphasize the integration of moving freshwater ecosystems into global carbon budget models, and their role as critical carbon sources.
- Balancing high-frequency data collection and the practicality of less frequent measurements in designing future environmental monitoring projects will be key for meeting land-use and water management policy and goals.

Table 1. Summary statistics of dissolved CO_2 as measured by lotic-SIPCO$_2$, the gas exchange velocity for CO_2 (kCO_2), and the estimated rate of CO_2 emission (FCO_2). Median values are listed with the interquartile range in parenthesis. Sites are listed in order of watershed area, from smallest to largest.

Site Name	Dissolved CO_2				
	µM	% Saturation	% Time Below Saturation	k_{CO2} (m d^{-1})	F_{CO2} (g C m^2 d^{-1})
Hubbard Brook Experimental Forest (HB)	26.6 (21.4)	164 (122)	32.6	15.9 (9.8)	0.8 (2.3)
Wednesday Hill Brook (WHB)	62.8 (15.5)	288 (78)	0.0	7.8 (3.1)	3.3 (1.9)
College Brook (CB)	85.2 (50.3)	506 (319)	1.4	6.7 (2.7)	5.7 (3.1)
Dube Brook (DB)	86.4 (88.2)	571 (515)	0.3	5.9 (3.2)	4.3 (3.8)
Cart Creek (CC)	136 (47.2)	734 (316)	0.0	5.6 (3.6)	5.8 (4.2)
Sawmill Brook (SB)	136 (47.2)	812 (345)	0.0	8.1 (3.6)	9.0 (4.6)
Trout Pond Brook (TPB)	50.6 (38.4)	280 (203)	4.0	4.4 (2.2)	1.6 (1.1)
Dowst Cate Forest (DCF)	65.5 (24.2)	338 (155)	0.7	11.6 (5.8)	4.6 (2.8)
Ipswich River (IR)	132 (79.3)	797 (559)	0.0	9.6 (4.3)	10.2 (3.6)
Lamprey River (LMP)	80.7 (32.5)	417 (232)	1.8	11.0 (6.7)	5.1 (3.6)
All sites	64.6 (36.7)	307 (223)	4.9	7.7 (6.0)	3.3 (3.6)

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MONITORING LAKE CYANOBACTERIA BLOOMS USING UNMANNED AERIAL SYSTEMS

C. BUNYON, B. FRASER, A. MCQUAID & R. CONGALTON

Billions of years ago, cyanobacteria were crucial to some of Earth's first lifeforms that produced oxygen and helped form the planet's atmosphere. More recently, a changing climate has led to increases in toxic blue-green algae blooms of cyanobacteria in New Hampshire lakes—popular summer getaways for Granite Staters and visitors, and important economic drivers for the state. Traditional monitoring of these blooms involves time-consuming water sampling and testing that can also expose environmental specialists to potential health risks. To overcome these challenges, the UNH Basic and Applied Spatial Analysis Lab developed a promising alternative for identifying aquatic cyanobacteria blooms—using unpiloted aerial systems, or drones, to identify cyanobacteria outbreaks, and their concentration levels, using spectral imaging data.

KEY TAKEAWAYS

Multispectral sensors on an unpiloted aerial system (UAS) proved over 90 percent effective in detecting cyanobacteria blooms—also known as harmful algal blooms—in New Hampshire lakes.

Relative to traditional water sampling methods, UAS monitoring reduces time and labor for monitoring, minimizes health risks to researchers and provides a more comprehensive understanding of water quality dynamics in real-time.

Cyanobacteria and Harmful Algal Blooms

Cyanobacteria, commonly known as blue-green algae, are a group of bacteria that obtain their energy through photosynthesis. They are known for their ability to thrive in various water bodies, including freshwater lakes, where they can form visible colonies known as algal blooms. Some species of cyanobacteria produce toxins harmful to aquatic life, pets, livestock and humans, leading to what are termed harmful algal blooms (HABs). These blooms can adversely affect water quality, ecosystem stability and public health.

Historically, monitoring and identifying cyanobacteria blooms has relied on the collection of lake water samples followed by laboratory analyses to determine cyanobacteria concentration. These methods, while effective, are labor- and time-intensive and can pose risks to researchers. Recent advancements in remote sensing and aerial survey technologies have presented new opportunities for monitoring environmental phenomena, but little research has focused on using unpiloted aerial system (UAS) technology.

Methodology

Researchers repeatedly assessed six New Hampshire lakes between May and September 2022 (**Fig. 1**). At each lake on each visit, a DJI M300 RTK drone (**Fig. 2**) with a MicaSense 10-band dual camera system was flown to collect multispectral imagery. Following image collection, water samples were collected at selected locations within the lake by a researcher in a canoe.

The samples were collected following the flight so that the imagery collection was not disturbed by the movement of the canoe through the water. Water samples were analyzed at the UNH Water Quality Analysis Lab to determine the concentrations of cyanobacteria in the water. Sample results were combined with the multispectral imagery to assess using a random forest digital image classification algorithm to determine if the imagery could accurately predict cyanobacteria concentrations.

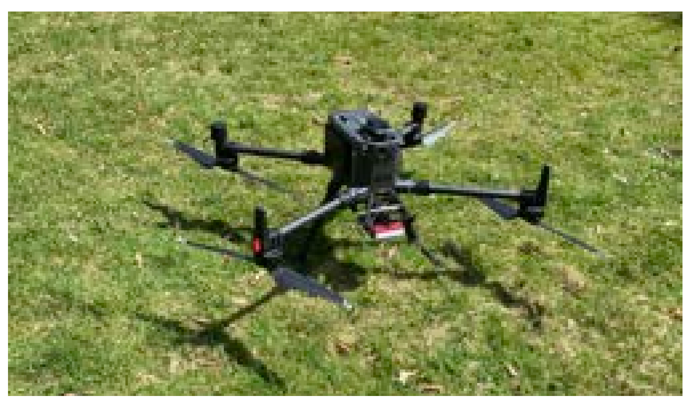
Results and Impacts

The methods achieved high overall classification accuracies for detecting cyanobacteria cell concentrations (93%), chlorophyll-a (87%) and phycocyanin levels (92%) from the remotely sensed imagery. These results demonstrate the potential of using UAS technology as a rapid, safe and efficient tool for monitoring algal blooms in freshwater systems.

Figure 1. Study site locations within the state of New Hampshire.

Credit: Christine Bunyon, M.S. Thesis, May 2023

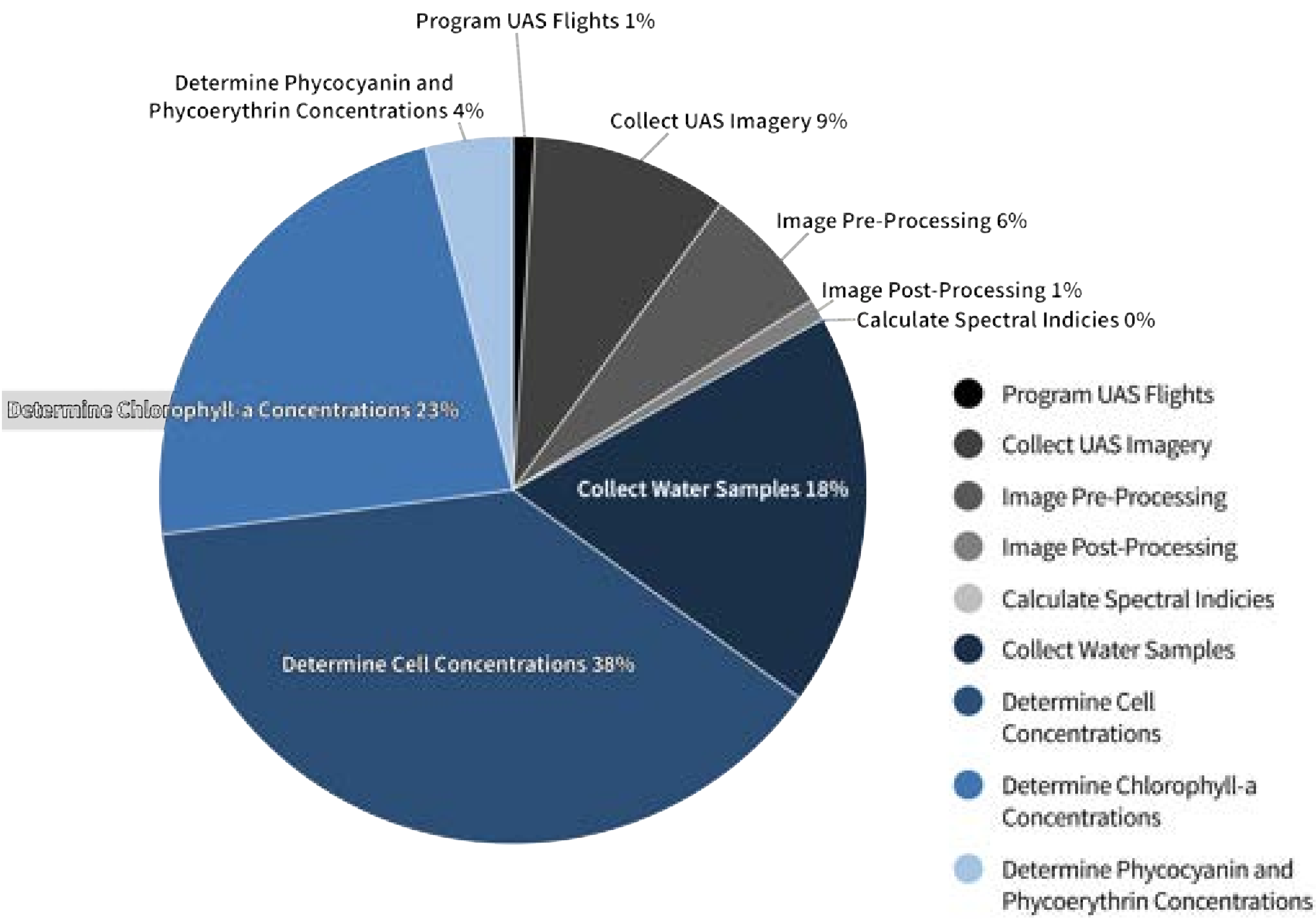
Figure 2. DJI Matrice 300 RTK drone.



The research also highlighted the utility of specific spectral indices and wavelengths—for example, the 475 nm wavelength and normalized green-blue/ red difference indices—in identifying cyanobacteria blooms. By providing a more immediate and detailed view of water quality conditions, UAS technology can assist environmental managers in making informed decisions, which are critical for long-term protection of public health and aquatic ecosystems (**Fig. 3**).

Additionally, there were valuable insights into the capabilities of using UASs for environmental monitoring and offer a model for similar research efforts in other regions. As cyanobacteria blooms become an increasingly significant concern due to climate change and nutrient runoff, the application of advanced monitoring technologies like UAS will be critical in safeguarding water resources and public health. The methods in this research represent significant advancement in environmental monitoring and offer a foundation for future studies and the implementation of UAS technology in combating the growing challenge of HABs globally.

Figure 3. Approximate comparison of the amount of time to complete tasks. Blue sections represent those associated with the collection and processing of water quality parameters. Grayscale sections represent those associated with the collection and processing of UAS parameters. Traditional water quality tasks took roughly 310 hours to complete while UAS tasks took roughly 65 hours to complete.



Credit: Christine Bunyon, M.S. Thesis, May 2023

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ASSESSING THE ROLE OF STREAMS IN METHANE EMISSIONS AND OXIDATION

A. K. ROBISON, W. M. WOLLHEIM, C. PERRYMAN, A. COTTER, J. MACKAY, R. VARNER, P. CLARIZIA & J. ERNAKOVICH

With 280 square miles of freshwater lakes and ponds and over 19,000 miles of rivers and streams in New Hampshire, water is critical to the health, economy and recreation of Granite Staters. However, with aquatic ecosystems annually releasing a similar amount of methane that humans release to the atmosphere each year, New Hampshire water may be playing a bigger role in greenhouse dynamics than previously thought. And while streams have been seen more as pipelines for moving methane rather than contributors, their roles in being a source or suppressor of methane is not well measured.

KEY TAKEAWAYS

Small streams were found to emit methane at rates comparable to lakes and wetlands, demonstrating that previous estimates of their contribution to methane emissions were likely undervalued.

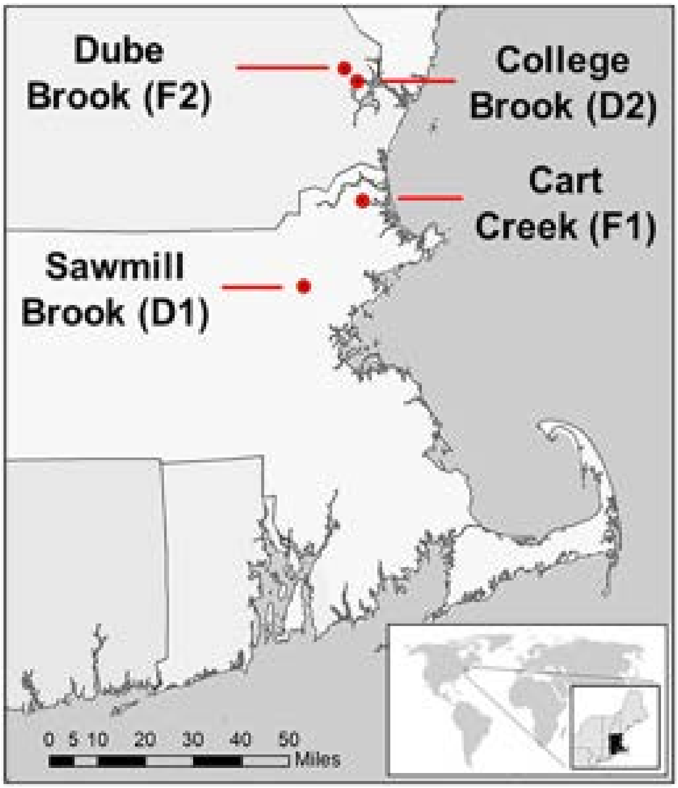
Unlike lakes and wetlands where methane is primarily emitted through ebullition, methane emissions in streams predominantly occurs through diffusion, where methane dissolved in the water is released from the water's surface into the atmosphere.

The presence of methane-producing and methane-consuming bacteria indicates active methane production and oxidation within stream ecosystems.

Background and Key Concepts

Aquatic bodies play different roles in the release of methane gas. Wetlands, lakes and reservoirs all release methane directly into the atmosphere, primarily through a process known as ebullition. In this process, methane literally bubbles out of the wetland and enters the atmosphere, contributing to the greenhouse gas effect. Rivers and streams haven't historically been viewed as nearly as important to the global methane cycle. Instead, they've been regarded as pipelines for moving material between bodies of water. This research focuses on identifying streams' precise role in the greenhouse gas emission process.

Figure 1. Locations of four study stream reaches in southeast New Hampshire and northeast Massachusetts.



Methodology

The research measured methane emissions and soil microbial communities within four streams in New Hampshire and Massachusetts (**Fig. 1**). These streams were chosen to represent contrasting land use conditions, including developed (suburban) and forested watersheds. The selected streams have been previously studied for nutrient and carbon cycling and land use impacts. Two streams, Sawmill Brook and College Brook, are in relatively developed suburban landscapes, while the other two, Cart Creek and Dube Brook, are predominantly in forest-covered landscapes.

Samples were collected from the four streams approximately each week, then analyzed at the Trace Gas Biogeochemistry Lab at the UNH Earth Systems Research Center. Statistical analyses were performed to assess differences in methane concentration, flux, isotopic composition and microbial communities between streams and sampling depths. The microbial communities in the streambeds were analyzed at the UNH Hubbard Center for Genome Studies to identify the presence of the types of bacteria that create methane (called methanogens) and oxidize methane to carbon dioxide (called methanotrophs).

Results and Impacts

This study sheds light on the significant role that small streams play in methane (CH_4) emissions within aquatic ecosystems. Despite their size, these streams emit CH_4 at rates comparable to larger water bodies when considering the area that they cover. However, what sets them apart is their unique isotopic signature compared to lakes and ponds. The research findings reveal that diffusive emissions—in which CH_4 is released from the water's surface into the atmosphere—are the primary mode of CH_4 transport in these streams (**Fig. 2**). The unique isotopic signature arises because the methane remains dissolved in the water, allowing it to be oxidized by methane oxidizing bacteria. This indicates a distinct pattern of CH_4 cycling in streams, emphasizing their importance in the overall methane budget.

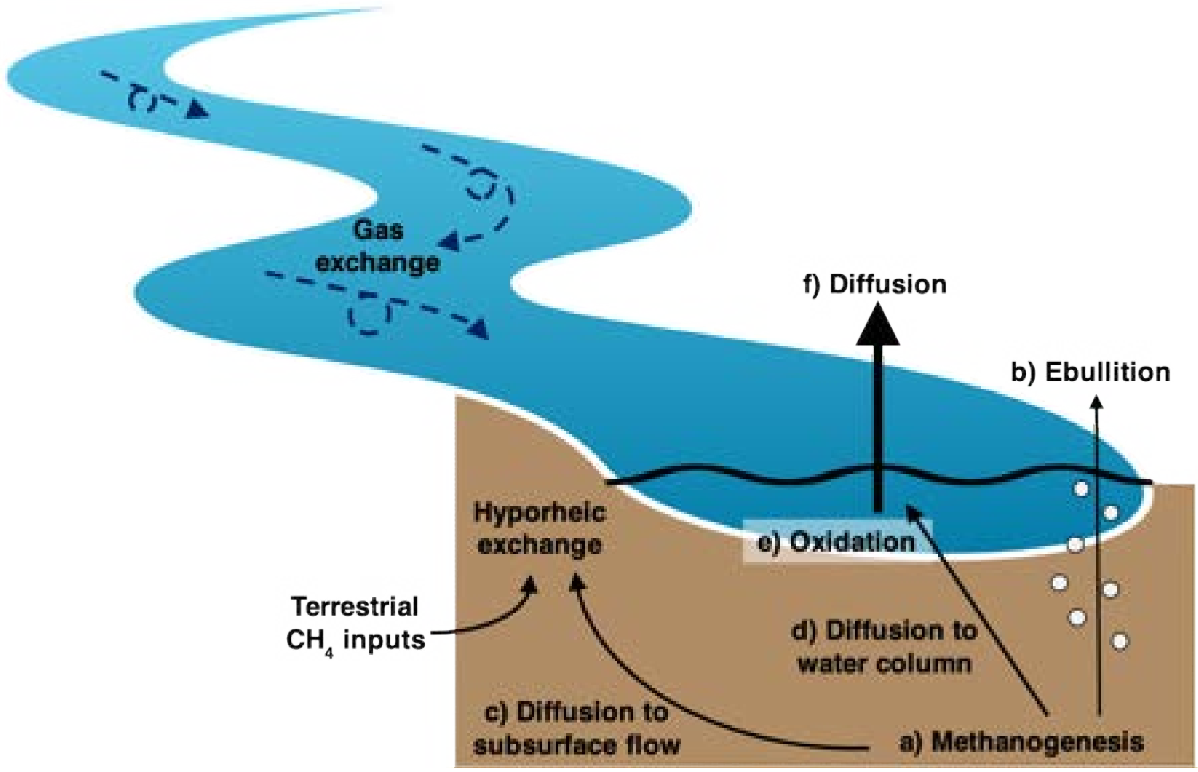
Collecting samples from Dube Brook in Madbury, NH.

Implications for the Future

The presence of methane-producing (methanogens) and methane-consuming (methanotrophs) bacteria highlights the dynamic nature of CH_4 production and oxidation within stream ecosystems. While the rapid transport of dissolved CH_4 limits its oxidation somewhat, the unique isotopic signature of emitted CH_4 differs from that of still water bodies indicating a relatively large proportion is in fact oxidized.

Understanding this unique isotopic signature is crucial for accurately incorporating streams and rivers into regional and global atmospheric CH_4 models. This research underscores the need for enhanced collaboration and interdisciplinary approaches to studying methane emissions in aquatic ecosystems. By examining the role of streams in methane cycling, this study helps set the stage for more comprehensive strategies to mitigate greenhouse gas emissions and address climate change challenges.

Figure 2. Proposed conceptual model of CH_4 production, transport, oxidation and emissions in stream ecosystems based on study results.



Note: The inherent flow and shallow nature of streams promotes hyporheic exchange and high gas exchange rates. This serves to limit bubble formation and promote the transport of dissolved CH_4 out of the sediments via diffusion and subsurface flow. While the dissolved CH_4 pool is exposed to oxidation, the proportion of CH_4 that is oxidized is limited by the relatively rapid exchange of water and gases in stream ecosystems. Most CH_4 is emitted via diffusion across the water-air interface in streams, and the limited exposure of this CH_4 pool results in relatively heavy dissolved CH_4 isotopic values. Because diffusive CH_4 emissions dominate the overall emission budget, the mean isotopic value of emitted CH_4 reflects this heavier signature and CH_4 isotopes in streams are enriched relative to other aquatic ecosystems.

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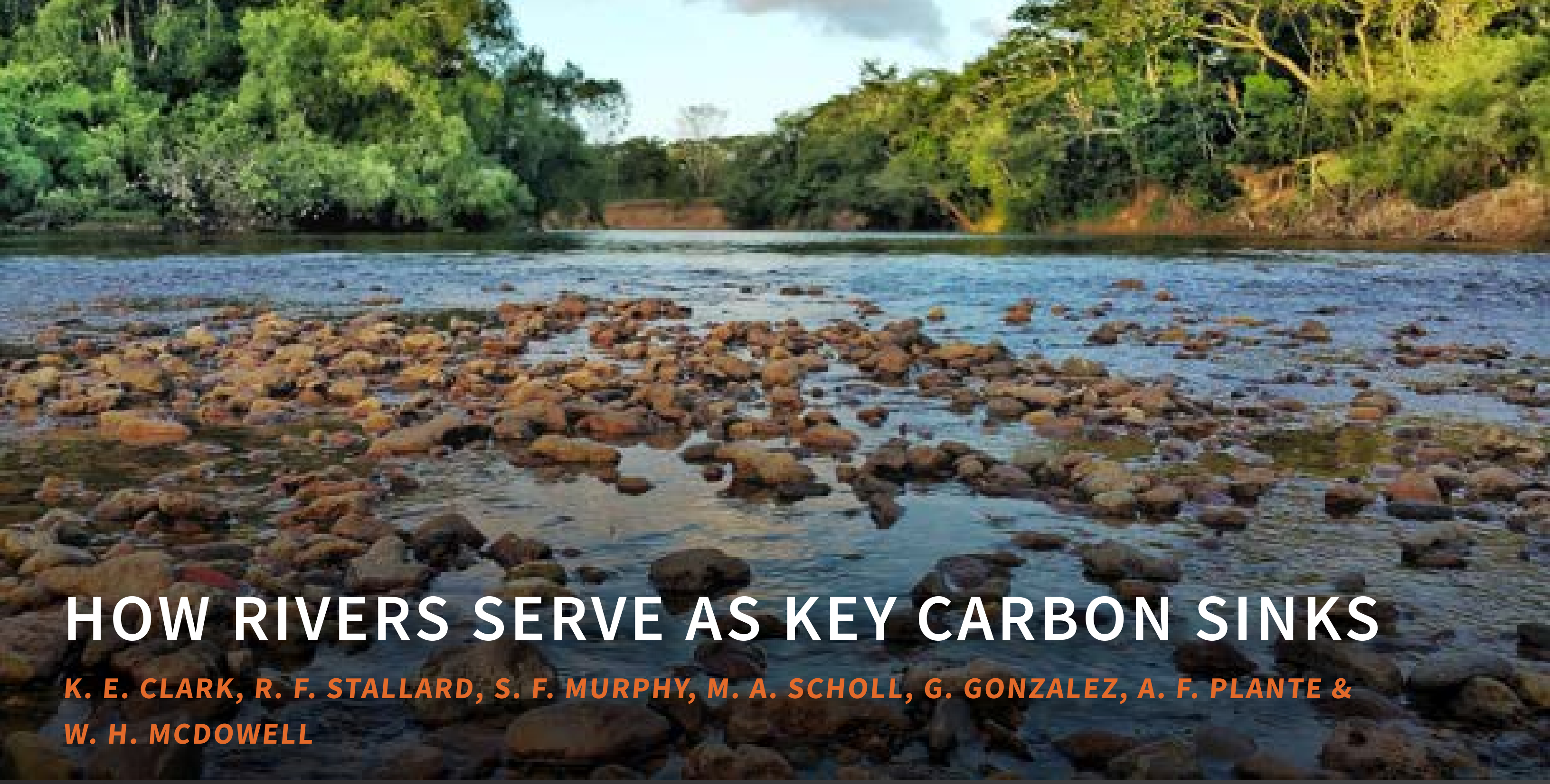


HOW RIVERS SERVE AS KEY CARBON SINKS

K. E. CLARK, R. F. STALLARD, S. F. MURPHY, M. A. SCHOLL, G. GONZALEZ, A. F. PLANTE & W. H. MCDOWELL

Rivers in tropical and temperate climates like New Hampshire are often celebrated for their biodiversity and value as ecotourism destinations. But they may also play a more critical function in the Earth's ecological balance than previously recognized by acting as natural carbon sinks—capturing and preventing organic carbon from converting into carbon dioxide, a potent greenhouse gas. The mechanism by which rivers play this pivotal role is still, however, not fully identified. One factor may be the manner in which rivers carry sediment from inland to the ocean.

KEY TAKEAWAYS

Tropical rivers act as significant carbon sinks, with over 65% of particulate organic carbon (POC) buried in ocean sediments.

Extreme rainfall events, which are becoming more frequent due to climate change, contribute to over half of the annual POC transfer from rivers to oceans.

The research helps place a greater emphasis on the role of rivers in the global carbon cycle and, ultimately, on their climate impacts.

Measuring Particulate Runoff

The research team analyzed water samples collected between 1991 and 2015 from the Luquillo Experimental Forest in Puerto Rico's El Yunque National Forest (**Fig. 1**), focusing on particulate organic carbon (POC) and sediment concentrations in the river water samples captured following major rainfall events. The researchers quantified the amounts of sediment and POC runoff, which they paired with river discharge data from the U.S. Geological Survey. Using this dataset, they were able to estimate particulate organic carbon yields, shedding light on the rivers' efficiency in carbon sequestration and the impact of extreme rainfall events on these processes.

Results and Impacts

The findings highlight rivers' remarkable capacity for carbon storage. For rivers emptying directly into the ocean, more than 65% of POC is buried in offshore sedimentary deposits (**Fig. 2 on pg. 32**). This process not only removes carbon from the atmospheric cycle but also highlights the critical role of these waterways in long-term carbon sequestration.

Impact of Extreme Rainfall

Research findings indicate that extreme rainfall events, which are growing more frequent and intense with global warming, are responsible for a significant share (52-60%) of the annual POC export by rivers. This underscores the vulnerability of these ecosystems to climate variability and the crucial role they play in buffering climate impacts.

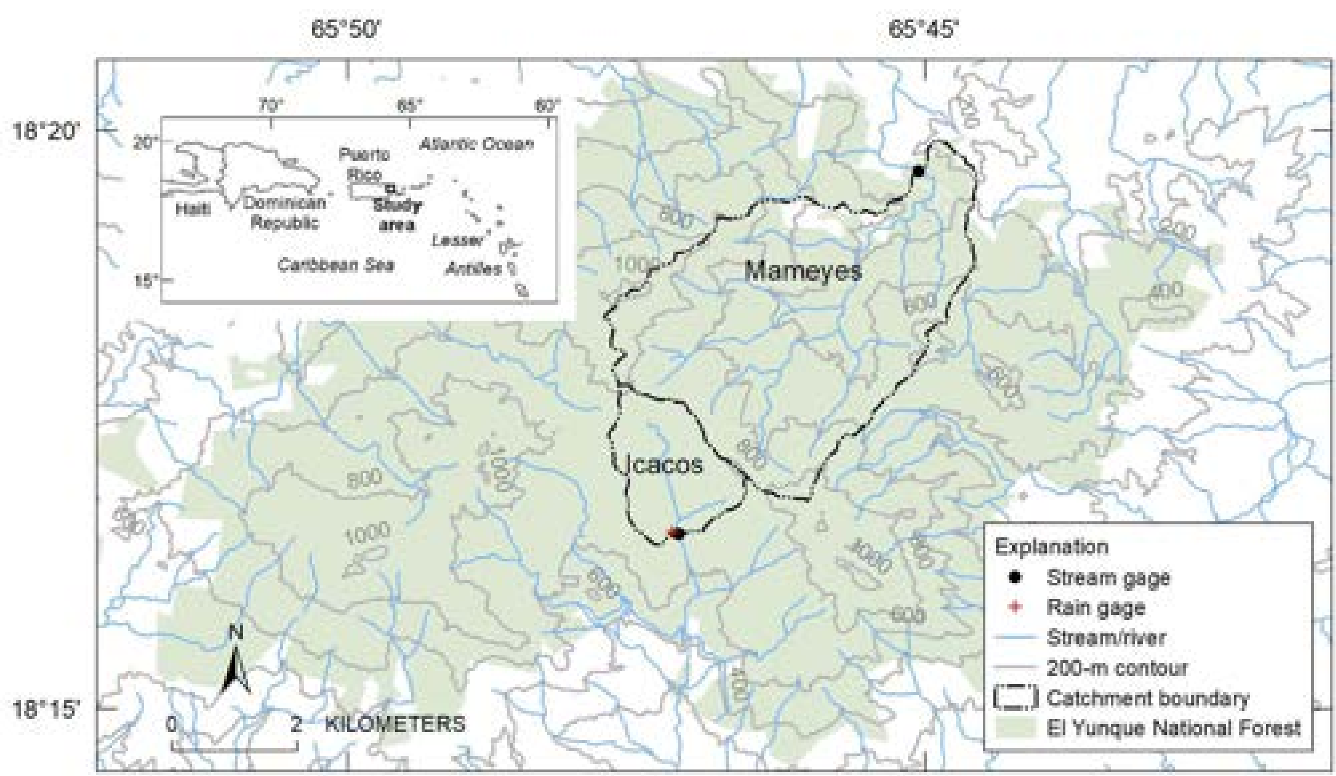
Reevaluating River Contributions

Findings from this study are helping update the underlying assumptions of prior models, which likely underestimated the contribution of rivers with less erodible, igneous and volcaniclastic bedrock. These rivers are now recognized as even more integral to the global carbon cycle than previously thought, necessitating a reevaluation of their role in ecological models and conservation strategies.

Implications for the Future

To address the broader implications of these findings, it is important to consider the role of temperate aquatic ecosystems, such as those in New Hampshire, in global carbon cycling. The substantial carbon sequestration capabilities identified in tropical rivers suggest similar mechanisms may be at work in the temperate zones too, albeit with different dynamics

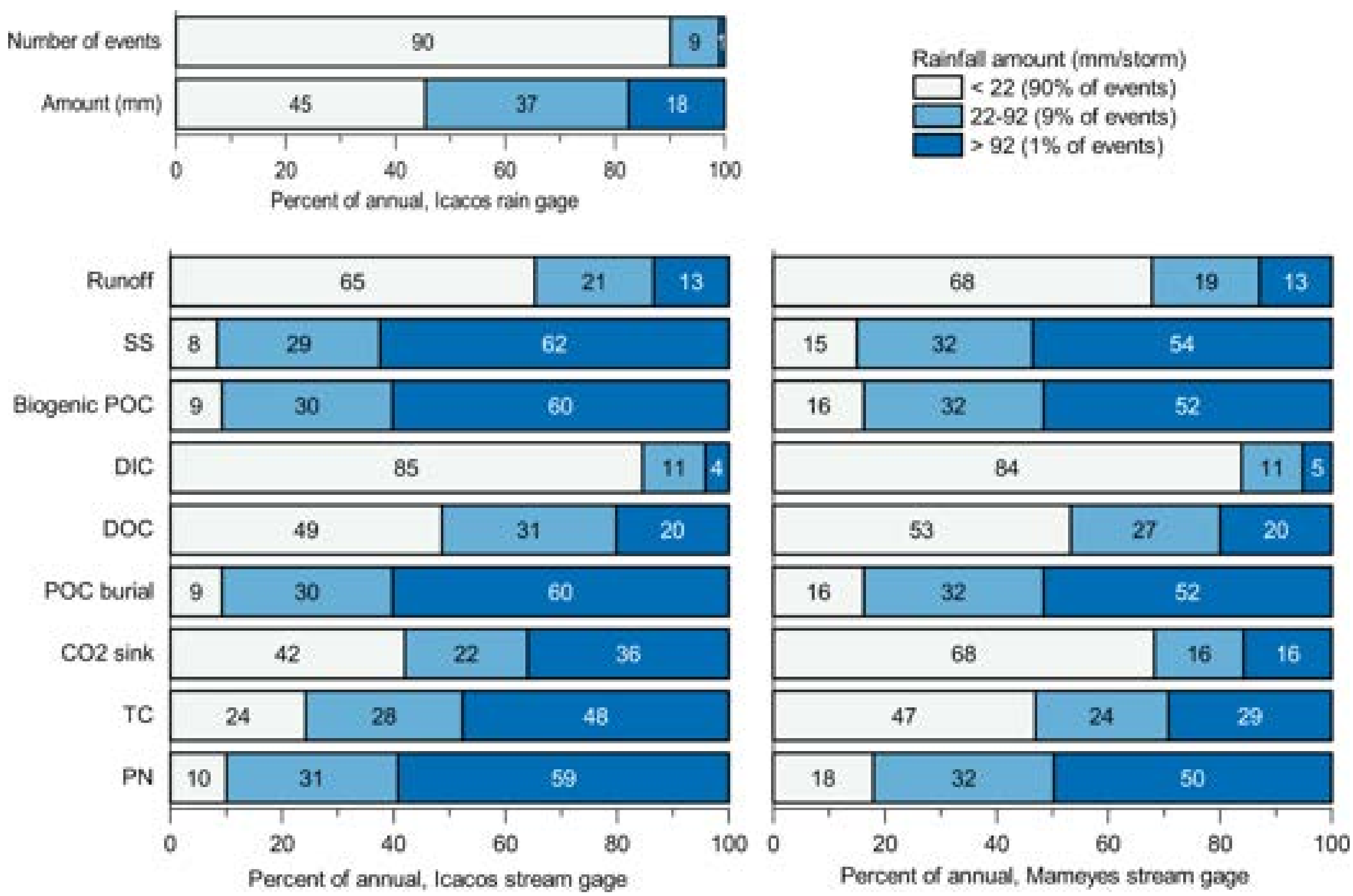
Figure 1. Map of the study catchments—the Mameyes and Icacos—located in El Yunque National Forest,Puerto Rico.



due to the variation in climate and vegetation. These temperate ecosystems, often rich in biodiversity and integral to local hydrological cycles, could also be pivotal in mitigating climate change through natural processes such as carbon capture. This underlines the necessity for a regional approach to monitoring and protecting riverine systems in New England, adapting conservation strategies to ensure these ecosystems can maintain their crucial role in carbon cycling.

Further research should focus on quantifying the carbon sequestration capacities of New England's rivers, with particular attention to how seasonal changes and extreme weather events impact organic carbon transport and deposition. Understanding these local dynamics will be essential for developing targeted management practices that safeguard these environments and contribute to broader efforts to mitigate climate change effects.

Figure 2. Percent contribution of annual runoff and river exports by rainfall event size for the Icacos and Mameyes Rivers.



Note: These exports are separated by rainfall amount as a percentage of annual total (SS suspended sediment, POC biogenic particulate organic carbon, DIC dissolved inorganic carbon, DOC dissolved organic carbon, POC burial estimated POC burial in ocean if biogenic POC_{burial} efficiency is estimated at 22%, CO2 sink estimated atmospheric carbon sink (POC_{burial} + DIC), TC total carbon (POC + DIC + DOC), PN particulate nitrogen).

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EXAMINING DRIVERS OF CARBON AND NITROGEN AVAILABILITY IN FRESHWATER ECOSYSTEMS AT DIFFERENT SPATIAL SCALES

H. M. FAZEKAS, J. BRUN & A. S. WYMORE

Freshwater ecosystems are integral components of the ecosystem and crucial for supporting biodiversity and providing ecosystem services. Streams and rivers are the conduits of energy and nutrients from landscapes to aquatic systems. These water bodies often reflect a complex interplay between their catchment characteristics—the landscape features that collect precipitation and direct it as runoff to streams, rivers and other water bodies—and the health and productivity of aquatic ecosystems, as well as broader environmental factors. However, the roles of climate, soil and watershed characteristics on the drivers of carbon and nitrogen availability in streams and rivers is not well identified, limiting a fuller understanding of how multilayered interactions play a role in freshwater biogeochemistry and water quality.

KEY TAKEAWAYS

Climate, watershed and soil characteristics are key mediators of carbon (C) and nitrogen (N) availability in streams, but their influence varies by scale—the different levels of geographical or spatial size at which observations and measurements of stream chemistry are taken and analyzed.

At broader scales, C and N variability is poorly explained, suggesting complex, scale-dependent processes.

Unique pathways and interactions between climate, soil and watershed characteristics control stream C and N across spatial scales, with hydrometeorological processes being a consistent driving force.

Background and Key Concepts

For this study, three scales were examined:

- **Continental Scale:** The broadest geographical scope of the study, looking at streams and rivers across the entire continental United States. At this scale, the study observes general patterns and drivers of stream chemistry that are applicable over vast regions.
- **Ecoregion Scale:** A more focused geographical area within the continental scale that shares similar ecological and climatic characteristics. This scale allows for the examination of stream chemistry within regions that have similar ecological features, climate and landscape forms.
- **Biogeoclimatic Region Scale:** An even more specific areas characterized by unique biological, geological and climatic conditions. This finer scale provides insights into how stream chemistry is influenced by localized conditions and interactions.

This study also examined direct and indirect drivers of nutrients and energy. Direct and indirect drivers refer to the pathways and mechanisms through which climate, soil, and watershed characteristics influence the concentrations of carbon and nitrogen in stream water.

- **Direct Drivers:** These are factors that have an immediate and measurable impact on stream chemistry. For example, the soil characteristics such as porosity or hydraulic conductivity (the ease in which fluid moves through a soil matrix) can directly affect the amount of total organic carbon (TOC) in streams by influencing the movement and filtration of water and carbon compounds through the soil into the waterways.
- **Indirect Drivers:** These factors influence stream chemistry through one or more intermediary steps or processes. For example, the study found that climate influences nitrate (NO_3-) concentrations indirectly through watershed characteristics. That is, climate factors such as precipitation patterns and temperature may not alter nitrate levels in the water directly, but instead, they impact other aspects such as vegetation growth or soil processes, which in turn affect how nitrates are transported into streams.

Methodology

The research integrated stream chemistry data on TOC and NO_3- from the United States Geological Survey with data from the Catchment Attributes and Meteorology for Large-sample Studies database. The initial dataset covered 671 basins across the contiguous United States that were selected for their minimal human impact, ensuring that observed chemical patterns were less likely to be anthropogenically altered. This larger dataset was used to compile and analyze more than 37,000 chemistry measurements taken from 459 streams and rivers, alongside landscape and climatic variables.

Results and Impacts

At the continental scale, the study uncovered that while climate, watershed and soil characteristics collectively explain a fraction of the variance in TOC and NO_3- concentrations, with 25% for TOC and a mere 6% for NO_3-, this coverage substantially increases at smaller spatial scales. Notably, the explained variance for TOC and NO_3- rises to 61% and 40%, respectively, when observed at narrower scales. This scale-dependent nature of environmental influence supports the hypothesis that broader scale evaluations capture a more diverse set of biogeochemical processes which are less discernible than those at localized scales.

Carbon Dynamics Across Scales

The direct and indirect drivers of stream chemistry unveiled scale-sensitive interactions. At the continental scale, carbon dynamics are modestly explained by environmental drivers; however, the intricacies of these dynamics become more pronounced at reduced spatial scales. Soil properties, such as hydraulic conductivity and porosity, were found to be significant direct predictors of TOC concentrations, highlighting the critical role of terrestrial–aquatic interfaces in biogeochemical cycling.

It is at the ecoregion and biogeoclimatic scales that the complexity of climate–soil interactions becomes evident. Notably, the impact of hydrometeorological forces like seasonality of precipitation play a contrasting role across scales, directly influencing carbon concentrations at broader scales and indirectly at finer scales via soil moisture interactions.

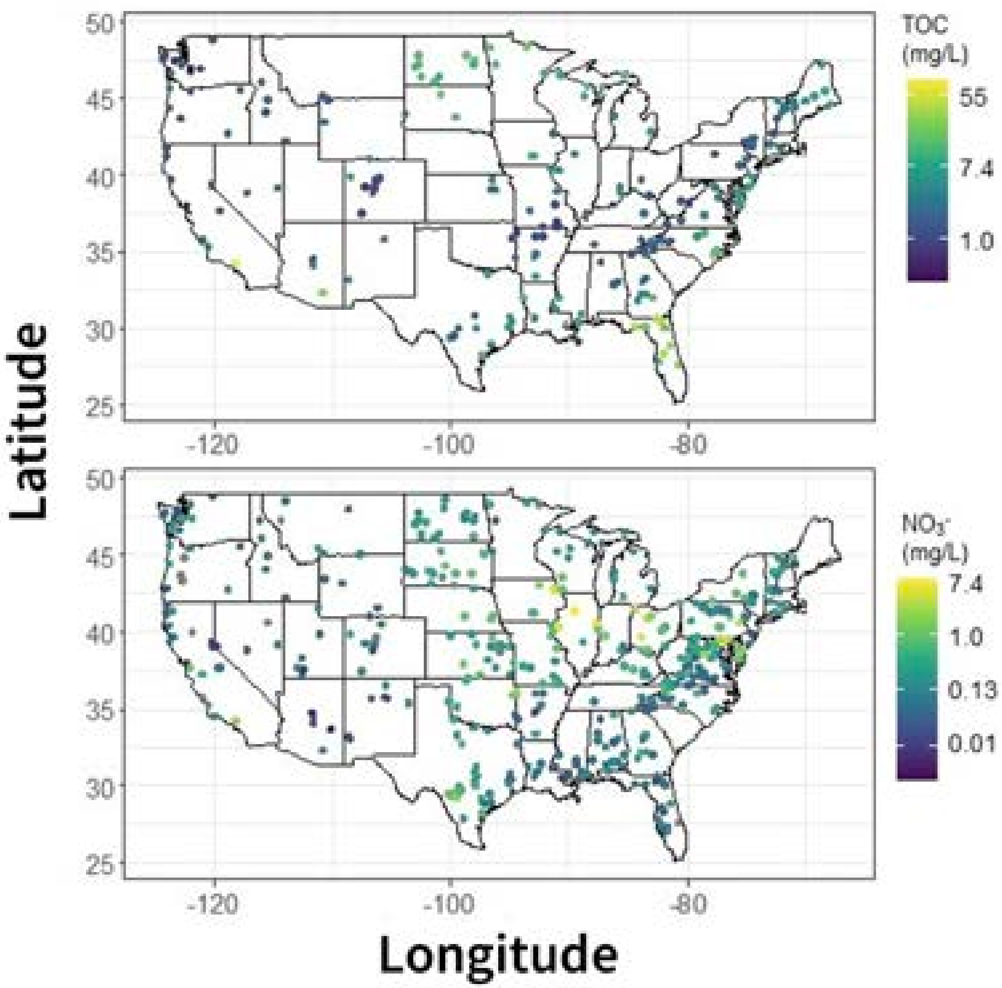
Nitrogen Dynamics Through the Lens of Scale

The study also sheds light on nitrogen dynamics, demonstrating strong associations with watershed attributes like forest cover and slope. These findings underscore the importance of physical catchment features in controlling nitrogen transport, a critical component for informing watershed management strategies. Climate's indirect effect on nitrogen, primarily through watershed characteristics, suggests that management efforts may need to focus on both the physical catchment structure and the broader climatic forces that modulate these characteristics.

Strategic Implications for Management

Insights from this study have significant implications for strategic environmental management. Policies and conservation efforts need to be fine-tuned to the spatial scale at which they are implemented to address the nuanced variations revealed in carbon and nitrogen dynamics. Soil conservation emerges as a priority in carbon-rich areas, while nitrogen transport concerns may call for an emphasis on watershed management.

Figure 1. Median total organic carbon (top) and NO3 − (bottom) concentrations (in mg/L) for streams used in partial least squares structural equation modeling (PLS-SEM) analyses.



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THE ROLE OF WATERSHEDS IN MITIGATING IMPACTS OF CLIMATIC EXTREMES

H. M. FAZEKAS, W. H. MCDOWELL, J. B. SHANLEY & A. S. WYMORE

As more is learned about rivers' role in affecting climate change, New England's watersheds are being seen as having greater impact on maintaining and restoring ecological balance. Watershed ecosystems—pivotal for their biodiversity and ecological services—also perform the essential function of modulating nutrient transport to downstream water bodies. The extent to which New England watersheds help regulate the flow and concentration of nutrients—especially during extreme weather events—remains an open question, the answer to which could help better understand rivers' roles in mitigating climate change.

KEY TAKEAWAYS

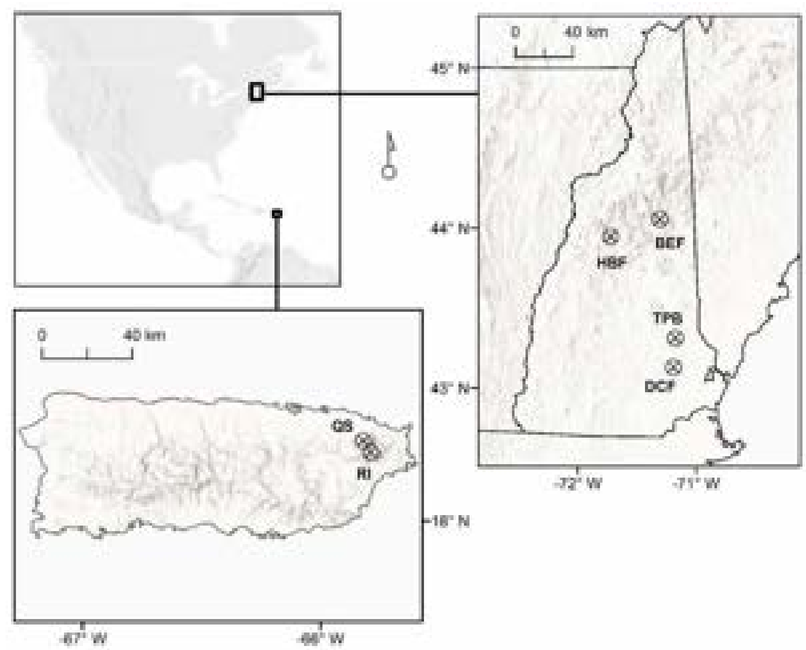
Extreme weather events, including droughts and heavy rainfall, can significantly alter nutrient loads in waterways, producing unpredictable effects on water quality.

Heavy precipitation events result in watersheds acting as "conveyor belts" that transport material to streams. Conversely, drier conditions increase nutrient concentration variability, resulting in greater ecological and chemical interactions that modify nutrient content before it's deposited downstream.

Methodology

The study developed a detailed analysis of sensor data from six distinct watersheds—four in New Hampshire and two in Puerto Rico—over 7 years (**Fig. 1**). These high-resolution data provided insights into how fluctuations in precipitation and temperature affect the relationship between nutrient concentration, including nitrate and dissolved organic matter, and water discharge—key indicators of the watershed's ability to transport and transform nutrients. That is, the various chemical, physical and biological processes that change the forms, structures and bioavailability of nutrients. By examining the concentration-discharge behavior in relation to weather anomalies, the study could deduce the underlying hydrological and biogeochemical processes that dictate nutrient mobility within these ecosystems.

Figure 1. Map of study sites in New Hampshire (HBF = Paradise Brook; BEF = Albany Brook; TPB = Trout Pond Brook; DCF = Dowst Cate Forest) and Puerto Rico (QS = Quebrada Sonodora and RI = Rio Icacos).



Results and Impacts

Nutrient Transport and Transformation

In conditions wetter than typical, the results indicate that New England's watersheds function akin to conveyor belts, transferring nutrients to other aquatic systems such as lakes and estuaries without significant transformation of those nutrients. Nutrients are delivered to downstream water bodies, where they can accumulate and impact water quality and the ecological integrity of these systems.

This accumulation can cause issues like eutrophication—the accumulation of nutrients like nitrogen and phosphorus in waterbodies leading to excessive plant and algal growth that depletes oxygen from the waterbody, harming other aquatic life. The result is degraded water quality and diminished ability of wetlands to naturally filter nutrients.

However, during drier and warmer periods, there appeared a stark increase in the variability of nutrient concentrations, suggesting the watersheds' capacity to act as transformers. That is, under these weather conditions, nutrients are likely retained and processed within a watershed, potentially reducing the risk of eutrophication in other aquatic ecosystems.

Impact of Climatic Extremes

The findings indicate that as extreme weather becomes more common, predicting the effect on water quality, particularly nutrient loads, is increasingly challenging. This unpredictability is a concern for New England's waterways, where nutrient concentrations are essential for the health of fisheries, food webs and the region's recreational appeal.

Land-use and Policy Implications

As research continues to show the influence of New England's watersheds on helping the region adapt to increasing climate extremes, rethinking and adapting land-use management strategies and public policy to leverage critical natural resources will be key. Additionally, the work shows the importance of policymakers to consider the way New England watersheds are impacted and impact the transfer of nutrients across waterbodies and landscapes, which can affect ecosystems and economies of the region.

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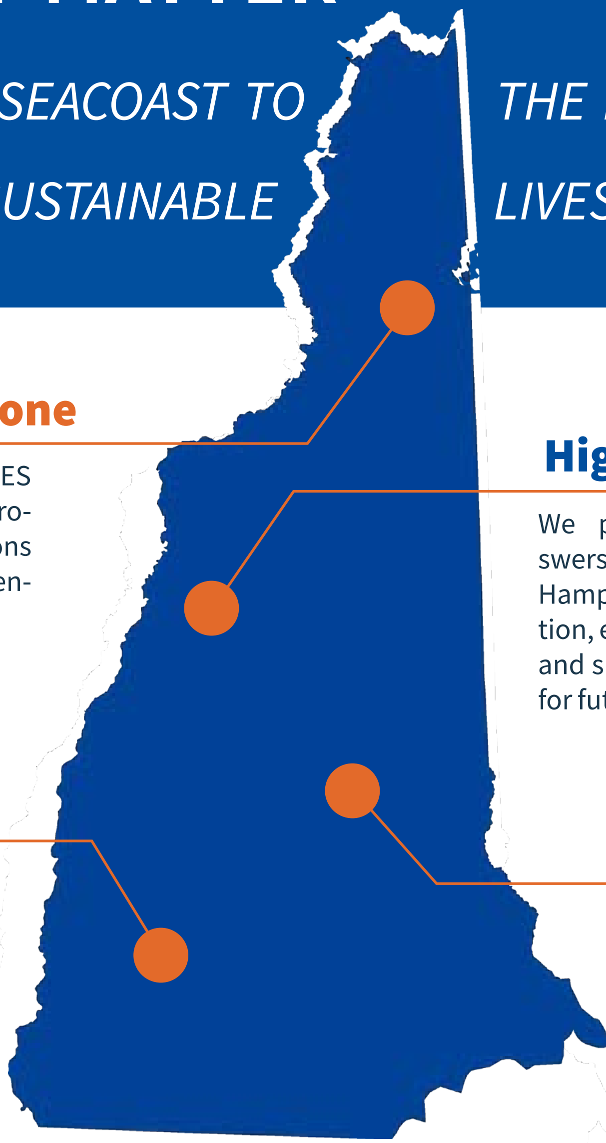
IMPACTS THAT **MATTER**

FROM THE SEACOAST TO THE NORTH WOODS,
SCIENCE FOR SUSTAINABLE LIVES & LIVELIHOODS



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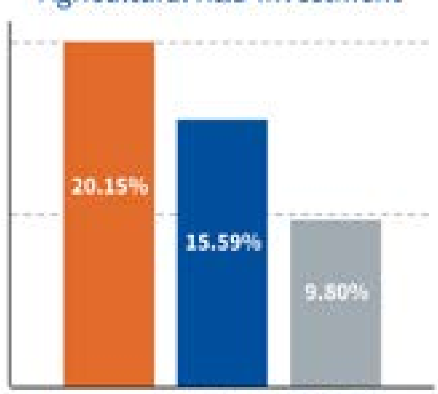
BY THE NUMBERS

The Experiment Station Supports:

52	Scientists
38	Graduate students, postdoctoral fellows
810	Research farm and forest acres
304	Research dairy cows
1,359,711	Stakeholders across New Hampshire

Annual Rate of Return on Agricultural R&D Investment



Source: Data from Plastina (2012), "Rates of return to public agricultural research in 48 states."

$23.8 million

in competitive federal, state, and industry grants awarded to Station scientists to further support locally important research.

A nearly **400%** return on initial federal and state investment.

FOR FURTHER READING & ACKNOWLEDGEMENTS

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The Lamprey River Hydrological Observatory: Water Chemistry Changes Amid Suburban Expansion

Wymore, A. S., Shattuck, M. D., Potter, J. D., Snyder, L., & McDowell, W. H. (2021). The Lamprey River Hydrological Observatory: Suburbanization and changing seasonality. Hydrological Processes, 35, e14131. https://doi.org/10.1002/hyp.14131

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Image and figure credits: Top image: Adam Wymore; Figure 1: Michelle Shattuck

Plant Responses to an Urbanization Contaminant

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Climate Change and Its Effects on Nitrogen Dynamics in Precipitation

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The Enhanced Pollution Filtration Abilities of Large Watersheds

Wollheim, W. M., Harms, T. K., Robison, A. L., Koenig, L. E., Helton, A. M., Song, C., Bowden, W. B., & Finlay, J. C. (2022). Superlinear scaling of riverine biogeochemical function with watershed size. Nature Communications, 13(1), 1230. https://doi.org/10.1038/s41467-022-28630-z

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Image and figure credits: Top image: Wil Wollheim; Figure 1: Wil Wollheim

Adapting an Open-source Carbon Dioxide Sensor for Streams and Rivers

Robison, A. L., Koenig, L. E., Potter, J. D., Snyder, L. E., Hunt, C. W., McDowell, W. H., & Wollheim, W. M. (2024). Lotic-SIPCO2: Adaptation of an open-source CO2 sensor system and examination of associated emission uncertainties across a range of stream sizes and land uses. Limnology and Oceanography: Methods, 22, 191–207. https://doi.org/10.1002/lom3.10600

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Image and figure credits: Top image: Drew Robison; Figure 1: Drew Robison; Figure 2: Drew Robison

Monitoring Lake Cyanobacteria Blooms Using Unmanned Aerial Systems

Bunyon, C. L., Fraser, B. T., McQuaid, A., & Congalton, R. G. (2023). Using imagery collected by an unmanned aerial system to monitor cyanobacteria in New Hampshire, USA, lakes. Remote Sensing, 15(11), 2839. https://doi.org/10.3390/rs15112839

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Image and figure credits: Top image: Ben Fraser; Figure 1: Christine Bunyon; Figure 2: Ben Fraser; Figure 3: Christine Bunyon

Assessing the Role of Streams in Methane Emissions and Oxidation

Robison, A. L., Wollheim, W. M., Perryman, C. R., Cotter, A. R., Mackay, J. E., Varner, R. K., Clarizia, P., & Ernakovich, J. G. (2022). Dominance of diffusive methane emissions from lowland headwater streams promotes oxidation and isotopic enrichment. Frontiers in Environmental Science, 9(791305). https://doi.org/10.3389/fenvs.2021.791305

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Image and figure credits: Top image: Wil Wollheim; Figure 1: Drew Robison; Insert image 1: Drew Robison; Figure 2: Drew Robison

How Rivers Serve as Key Carbon Sinks

Clark, K. E., Stallard, R. F., Murphy, S. F., Scholl, M. A., González, G., Plante, A. F., & McDowell, W. H. (2022). Extreme rainstorms drive exceptional organic carbon export from forested humid-tropical rivers in Puerto Rico. Nature Communications, 13(1), 2058. https://doi.org/10.1038/s41467-022-29618-5

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Examining Drivers of Carbon and Nitrogen Availability in Freshwater Ecosystems at Different Spatial Scales

Fazekas, H. M., McDowell, W. H., Potter, J. D., & Wollheim, W. M. (2023). Direct and indirect drivers of stream chemistry responses to climate and anthropogenic changes. Global Biogeochemical Cycles, 37(1), e2022GB007198. https://doi.org/10.1029/2022GB007198

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The Role of Watersheds in Mitigating Impacts of Climatic Extremes

Fazekas, H. M., McDowell, W. H., Shanley, J. B., & Wymore, A. S. (2021). Climate variability drives watersheds along a transporter-transformer continuum. Geophysical Research Letters, 48, e2021GL094050. https://doi.org/10.1029/2021GL094050

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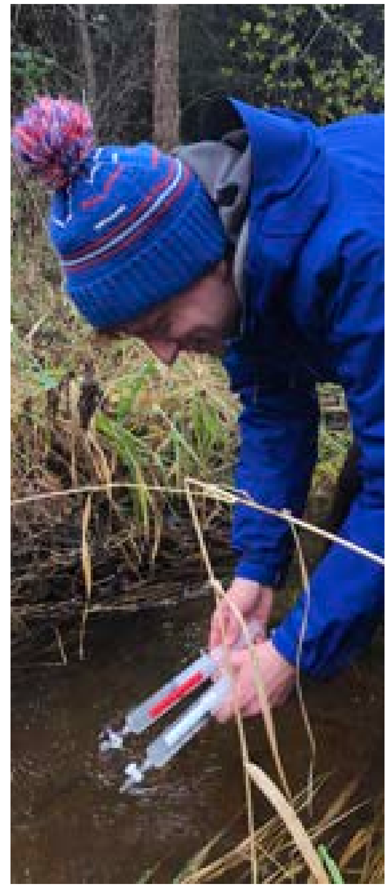

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