

A photograph of a forest stream with a white title box overlaid on top. The stream is surrounded by trees and ferns, and the water is dark and reflective. The title box contains the main title of the report in blue text.

# Spatial and Temporal Variability of Fish Assemblages in Acidified Streams: Implications for Long-Term Monitoring

Summary Report | Report Number 19-29 | May 2019

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# **Spatial and Temporal Variability of Fish Assemblages in Acidified Streams: Implications for Long-Term Monitoring**

*Summary Report*

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## Notice

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## Abstract

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Numerous studies have established strong linkages between acidic deposition, soil and surface-water acidification, and toxicity to aquatic biota. Little is known, however, about the effects of acidification on fish assemblages in headwater streams because they are highly variable and pre-acidification data are often lacking. The primary purpose of this study was to describe spatial and interannual (temporal) variability of fish assemblages in headwater streams affected by acidification so that future recovery targets and monitoring strategies can be established. Fish communities and water chemistry were sampled at 48 headwater streams in the Western Adirondack Mountains of New York State during the summers of 2014–2016 to characterize the present-day condition of water quality and local fish assemblages. Additionally, data from six Adirondack streams that were sampled annually from 2014–2016 were combined with data from seven streams in the Catskill Mountain region that were sampled annually for three or more years for an analysis of temporal variability. Inorganic monomeric aluminum concentrations ( $[Al_i]$ , the toxic form of aluminum  $[Al]$ ) were less than 1.0 micromoles per liter ( $\mu\text{mol L}^{-1}$ ), between 1.0 and 2.0  $\mu\text{mol L}^{-1}$ , and greater than 2.0  $\mu\text{mol L}^{-1}$  in 79%, 13%, and 8% of the 48 Adirondack streams, respectively. Richness, abundance, and biomass of fish assemblages were negatively related to  $Al_i$  concentrations. In streams with  $Al_i$  concentrations less than 1.0  $\mu\text{mol L}^{-1}$ , species richness, density, and biomass averaged 2.0 species, 444.2 fish/0.1 acre (ha), and 1924.4 grams (g)/0.1 ha, respectively, and the density and biomass of Brook Trout populations averaged 280.8 fish/0.1 ha and 1384.0 g/0.1 ha. These values may provide a reasonable approximation of fish community conditions prior to anthropogenic acidification and can be used as targets for assessing future recovery of acidified streams. A power analysis that considered 21 fish metrics indicated a strong negative relation between interannual metric variability and statistical power for detecting change over time. Large differences were identified in the sample size necessary to achieve adequate power (0.8) depending on the metric utilized. In general, greater statistical power was obtained from metrics based on entire fish communities and from metrics standardized by reach length or sampling effort. Given the variability observed in our dataset, most metrics could detect a change of 30% with moderate effort, suggesting this may be an appropriate goal for future monitoring. Together, knowledge of biological recovery targets and the statistical power obtained from various fish metrics can be used to develop the most effective strategies for monitoring and assessing biological recovery in New York State streams.

## Keywords

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Acid Deposition; Adirondack Mountains; Streams; Fish Assemblages; Water Chemistry, Inorganic Monomeric Al; Monitoring; Temporal Variability; Power Analysis

## Acknowledgments

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Baldigo, B. P., George, S. D., Lawrence, G. B., & Paul, E. A. (2018). Acidification impacts and goals for gauging recovery of Brook Trout populations and fish communities in streams of the Western Adirondack Mountains, New York, USA. *Transactions of the American Fisheries Society*, 148, 373-392, <https://doi.org/10.1002/tafs.10137>.

For more information on the temporal variability of stream fish assemblages summarized in this report, please see the full journal article in *Ecological Indicators*. The full citation for this article is:

George, S. D., Baldigo, B. P., & Stich, D. S. (2019). Temporal variability in stream fish assemblage metrics and implications for long-term monitoring. *Ecological Indicators*, 101, 661-669, <https://doi.org/10.1016/j.ecolind.2019.01.055>.

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# 1 Focus

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The primary purpose of this study was to describe the spatial and interannual (hereafter ‘temporal’) variability of fish assemblages in headwater streams affected by acidification. Fish communities and water chemistry were sampled at 48 headwater streams in the Western Adirondack Mountains of New York State during the summers of 2014–2016. The resulting data were used to characterize current stream water quality and the condition of local fish assemblages. These findings were assessed to identify targets that could be used to gauge biological recovery expected to result from decreased levels of acidic deposition.

Six of these 48 Adirondack streams were sampled annually from 2014–2016. Data from these six sites, as well as comparable data from seven streams in the Catskill Mountain region (which were sampled annually for three to six years), were used to quantify the temporal variability in 21 fish metrics. This information was used to conduct a power analysis and determine the degree of change that could be detected in fish communities using the different monitoring metrics. Together, knowledge of biological recovery targets and the statistical power obtained from various fish metrics can be used to develop the most effective strategies for monitoring and assessing biological recovery in streams of New York State.

## 2 Context

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Acidic deposition has been one of the greatest threats to aquatic and terrestrial ecosystems in parts of Eastern North America over the past half century. Numerous studies have established strong linkages between acidic deposition, soil and stream acidification, and toxicity in headwater streams (Baldigo et al., 2007; Driscoll et al., 2003; Driscoll et al., 2001). Since the 1980s, reduced emissions of sulfur and nitrogen oxides have decreased the acidity of wet deposition in many acid-impacted areas (Strock et al., 2014). As a result, accompanying improvements in surface water chemistry have been documented in the Adirondack and Catskill Mountain regions of New York State (Driscoll et al., 2016; Lawrence et al., 2011; McHale et al., 2017; Waller et al., 2012). The recovery of biological communities in headwater streams, however, has been difficult to document because of a paucity of information on the past and present condition of fish assemblages in these regions.

There are several reasons why fish communities in headwater streams have not been adequately characterized. Many are located in remote and rugged areas where gaining access and conducting fish surveys are difficult (Figure 1). Furthermore, it is challenging to adequately sample the estimated 75,439 kilometers (km) of first-order streams in New York State, which comprise 59% of all stream length in the State (USGS, 2017). More importantly, environmental conditions such as discharge, temperature, and water chemistry can fluctuate rapidly in headwater streams, and as a result, fish populations and communities are frequently in a transitional state between disturbances. This instability means that even in the absence of anthropogenic stressors, temporal variability of fish communities in headwater streams is high and the statistical power to detect anthropogenic degradation or long-term change in these communities is low. As a result, long-term monitoring programs related to acidic deposition effects and potential recovery have largely avoided routine assessment of fish communities in headwater streams.

This pervasive lack of information permits only limited understanding of the effects of acidification on stream-fish assemblages and impedes efforts to quantify temporal trends and potential recovery in streams that are becoming less acidic. Information is needed on the current status and temporal variability of fish assemblages in headwater streams to refine stream fish-chemistry relations, assess future recovery from acidification, and to develop long-term monitoring strategies for detecting changes in these assemblages.

**Figure 1. A headwater stream in the Western Adirondacks**

Silver Run in the Moose River Plains where fish assemblages were surveyed in 2014.

*Source photo credit Barry Baldigo.*



### **3 Goals and Objectives**

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There were two primary objectives of this investigation. The first was to increase understanding of the past and present effects of acidic deposition on fish assemblages in streams of the Western Adirondack Mountains. Specific goals associated with this objective were to (1) describe the present-day severity and extent of impaired stream chemistry; (2) quantify the present-day condition of fish assemblages; (3) identify apparent chemical thresholds for fish impacts; and (4) identify potential biological targets that can be used to gauge the recovery of fish assemblages in streams of the Western Adirondacks. The second objective was to assess the temporal variability of fish assemblages in headwater streams to better inform future monitoring programs. Specific goals associated with this objective were to identify patterns in temporal variability among a suite of 21 candidate fish metrics calculated from streams historically affected by acidic deposition, and determine the degree of change that could be detected in these metrics over various sampling regimes.

## 4 Study Area and Methods

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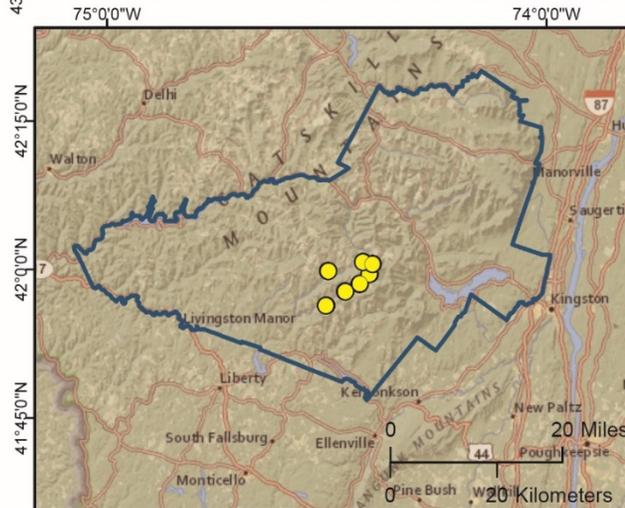
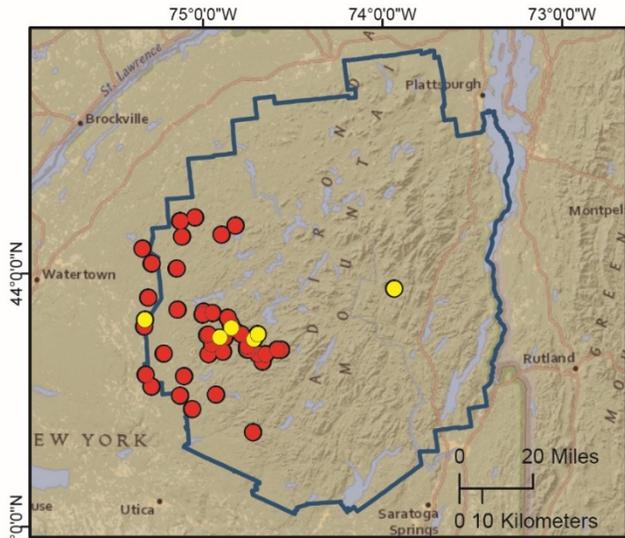
### 4.1 Relations Between Fish Assemblages and Water Chemistry

The Adirondack Mountain region is located in Northern New York State. The western portion of the region is characterized by shallow soils and underlying geology that impart naturally low acid-buffering capacity, resulting in high vulnerability to acidification. Forty-eight study streams were selected from a larger subset of previously studied streams to encompass a range of acid-base chemistry. All study sites were low-order streams with drainage areas between 0.43 and 17.3 km<sup>2</sup>. Except for Durgin Brook in the upper Hudson River basin, all sites were located in the Black River and Oswegatchie River basins of the Western Adirondacks (Figure 2).

Quantitative multi-pass electrofishing surveys were conducted in the 48 Adirondack study streams during the summers of 2014–2016. Forty-two of these streams were sampled once, while six of these streams were sampled annually during three consecutive summers (2014–2016) to quantify temporal variability. The reaches for most fish surveys ranged from 20 to 35 mean channel widths in length. The reach length and widths of 10 evenly spaced transects were measured and used to calculate mean width and total sampled area. Fish were collected from seine-blocked reaches during three or four consecutive passes using a backpack electrofisher and three to five netters. All fish were identified to species, weighed, and measured (total length) (Figure 3). Occasionally, the lengths and weights for small fish of highly abundant species were obtained from at least 30 individuals across their length range; after which, pooled weights and counts were recorded by species. All fish were returned to the stream after processing.

**Figure 2. Map of stream sites where fish surveys were conducted**

The 48 stream sites sampled in the Adirondack Mountains as part of the fish assemblage-water chemistry assessment (top panel) and the 13 stream sites in the Adirondack and Catskill Mountains where three or more consecutive annual surveys were conducted to assess temporal variability in fish assemblages (yellow points in both panels).



**Figure 3. Northern Pearl Dace and Brook Trout**

A Northern Pearl Dace *Margariscus nachtriebi* (top)—one of the less common species encountered during the Adirondack stream surveys, and a Brook Trout *Salvelinus fontinalis* (bottom)—encountered in 78% of the Adirondack stream surveys.

*Source photo credit Scott George.*



A single one-liter grab water sample was collected from all streams during each summer fish survey in 2014–2016. Samples were analyzed at the U.S. Geological Survey Soil and Low Ionic-Strength Water Quality Laboratory in Troy, NY for pH, acid-neutralizing capacity (ANC), calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), sodium ( $\text{Na}^+$ ), potassium ( $\text{K}^+$ ), sulfate ( $\text{SO}_4^{2-}$ ), nitrate ( $\text{NO}_3^-$ ), chloride ( $\text{Cl}^-$ ), dissolved organic carbon (DOC), silicon (Si), ammonium ( $\text{NH}_4^+$ ), total monomeric Al, and organic monomeric Al according to USEPA approved methods. Standard operating procedures for these analyses are available at <https://www.sciencebase.gov/catalog/item/55ca2fd6e4b08400b1fdb88f> (accessed 3/26/19). Inorganic monomeric Al ( $\text{Al}_i$ ) concentration was estimated as total monomeric Al concentration minus organic monomeric Al concentration, and any negative values were converted to zero. Inorganic aluminum is a form of Al that is mobilized under low pH conditions and causes toxicity to aquatic biota at values greater than  $2.0 \mu\text{mol L}^{-1}$  (Baldigo et al., 2007; Driscoll et al., 2001).

## 4.2 Temporal Variability and Power Analysis

Data from the six Adirondack sites that were sampled annually from 2014–2016 were combined with data from seven sites sampled annually in the Catskill Mountain region of Southeastern New York (collected as part of a separate study) for an analysis of temporal variability (Figure 2). The Catskill sites were of similar drainage area and elevation to the Adirondack sites and have been similarly affected by acidic deposition. Their inclusion in the study created a larger and more spatially representative dataset for subsequent analyses. The data from these 13 sites were used to calculate 21 fish metrics as follows. The number and mass of fish captured during each pass were used to estimate abundance and biomass for each species and the entire community at each site using a maximum-likelihood population estimator. The resulting estimates of abundance and biomass for the entire community and Brook Trout *Salvelinus fontinalis* populations were divided by the total area sampled in each survey to produce estimates of density and biomass per unit area, and divided by the sampled reach length to produce estimates of density and biomass per unit of stream length. Additionally, the number and mass of fish captured during the first electrofishing pass of each survey were used to produce “single-pass” density and biomass metrics by reach area and reach length for the entire community and for Brook Trout populations. Similarly, first-pass abundance and mass data were standardized by electrofishing time to produce catch-per-unit-effort (CPUE) estimates of density and biomass for the entire community and the Brook Trout populations. Finally, species richness was calculated as the number of species captured during each survey.

The temporal variability of each metric was calculated for each site across years using the coefficient of variation (CV). Metrics with a higher mean CV (calculated as the average of the CV from each of the 13 sites) exhibit greater annual variability while those with a lower mean CV exhibit less variability among years. Temporal variability is problematic because it can obscure long-term trends and may not represent effects from an anthropogenic stressor or indicate a change in resource condition. Metrics with lower temporal variability have the potential to achieve greater statistical power (the probability of rejecting a false null hypothesis or detecting a given change in resource condition), and therefore, may be desirable for use in long-term monitoring programs. To test this hypothesis, a simulation-based power analysis was used to determine the number of sampling events (i.e., years) at the 13 sites needed to detect various degrees of change (effect sizes) from the existing dataset with a power of 0.8. Detection at this level is interpreted as an 80% chance of detecting a given change in resource condition and is commonly used as a benchmark of an adequately powered study (Cohen, 1992).

## 5 Project Findings

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### 5.1 Relations Between Fish Assemblages and Water Chemistry

The density and biomass of all species populations can be calculated from the raw survey data available in George and Baldigo (2018). Brook Trout and Creek Chub *Semolitis atromaculatus* were observed in 78% and 33% of the surveys, respectively, and no other fish species were observed in more than 20% of the surveys. Species richness at the 48 study streams ranged from zero species in eight streams to a high of nine species at Durgin Brook in the upper Hudson River basin, but otherwise richness was limited to a maximum of five or six species in streams of the Black River and Oswegatchie River drainage basins.

Concentrations of  $Al_i$  were less than  $1.0 \mu\text{mol L}^{-1}$ , between  $1.0$  and  $2.0 \mu\text{mol L}^{-1}$ , and greater than  $2.0 \mu\text{mol L}^{-1}$  in 79%, 13%, and 8% of the 48 streams, respectively, during summer 2014–2016 (summer 2004 chemistry data were used for one site, see Baldigo et al. [2018]; Table 1 for more details). The richness, density, and biomass of fish assemblages were generally reduced at sites with elevated summer  $Al_i$  concentrations. No fish were captured from the four streams with  $Al_i$  concentrations greater than  $2.0 \mu\text{mol L}^{-1}$  (Table 1, Figure 4). Except for one stream site (with five fish species and exceptionally high DOC concentrations), only one species was observed in the other five streams with  $Al_i$  concentrations between  $1.0$  and  $2.0 \mu\text{mol L}^{-1}$ , compared to a mean richness of two species in streams with  $Al_i$  concentrations less than  $1.0 \mu\text{mol L}^{-1}$ . Mean fish density was zero in all four streams with  $Al_i$  concentrations greater than  $2.0 \mu\text{mol L}^{-1}$ , only 59.8 fish/0.1 ha in streams with  $Al_i$  concentrations between  $1.0$  and  $2.0 \mu\text{mol L}^{-1}$ , and 444.2 fish/0.1 ha in streams with  $Al_i$  concentrations less than  $1.0 \mu\text{mol L}^{-1}$ . Mean fish biomass was zero in four streams with  $Al_i$  concentrations greater than  $2.0 \mu\text{mol L}^{-1}$ , only 588.6 g/0.1 ha in streams with  $Al_i$  concentrations between  $1.0$  and  $2.0 \mu\text{mol L}^{-1}$ , and 1924.4 g/0.1 ha in streams with  $Al_i$  concentrations less than  $1.0 \mu\text{mol L}^{-1}$ .

Patterns in Brook Trout density and biomass generally mirrored those of entire fish communities.

Mean Brook Trout density was zero in streams with summer  $Al_i$  concentrations greater than  $2.0 \mu\text{mol L}^{-1}$ , 15 fish/0.1 ha in streams with  $Al_i$  concentrations between  $1.0$  and  $2.0 \mu\text{mol L}^{-1}$ , and 280.8 fish/0.1 ha in streams with  $Al_i$  concentrations less than  $1.0 \mu\text{mol L}^{-1}$  (Table 1, Figure 4). Mean Brook Trout biomass

was zero in streams with concentrations greater than 2.0  $\mu\text{mol L}^{-1}$ , only 303.3 g/0.1 ha in streams with  $\text{Al}_i$  concentrations between 1.0 and 2.0  $\mu\text{mol L}^{-1}$ , and 1384.0 g/0.1 ha in streams with  $\text{Al}_i$  concentrations less than 1.0  $\mu\text{mol L}^{-1}$ . Additional information on the relations between fish assemblages and other summer water chemistry parameters (e.g., pH and ANC) as well as springtime water chemistry parameters are available in Baldigo et al. (2018).

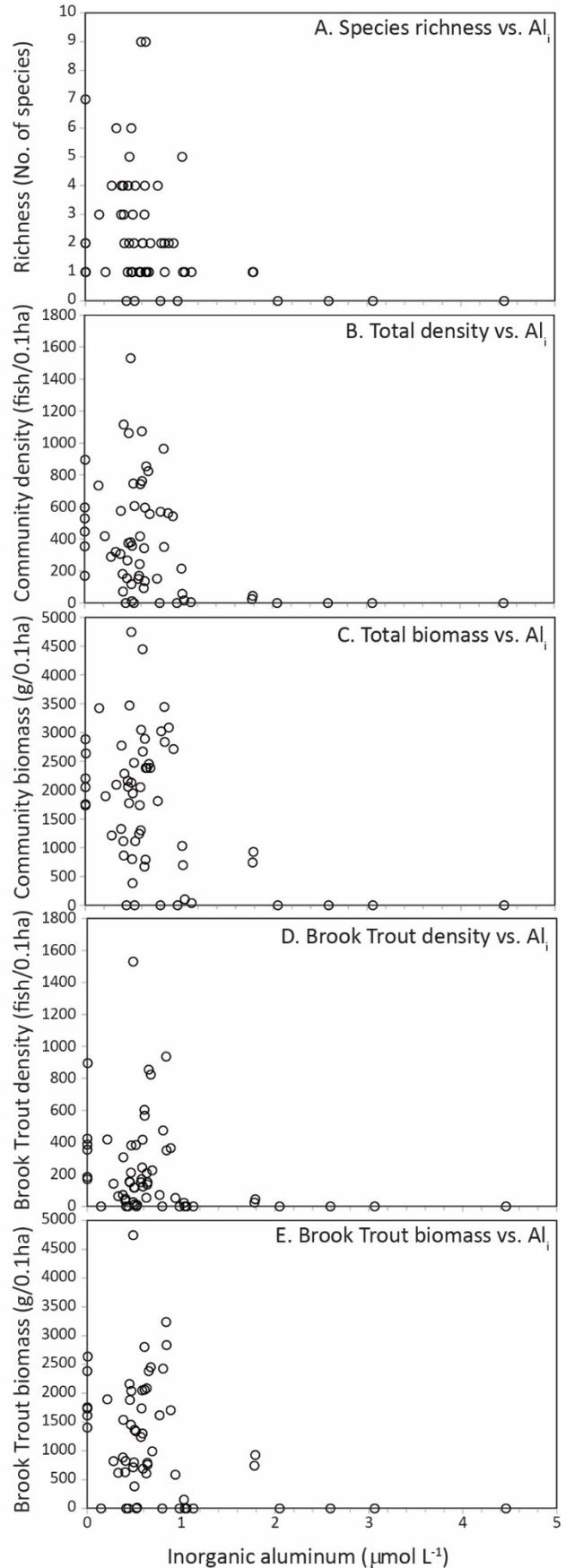
**Table 1. Fish metrics by inorganic monomeric Al ( $\text{Al}_i$ ) class**

Mean fish metric by summer  $\text{Al}_i$  concentration class from 48 Adirondack streams.

	Inorganic aluminum class ( $\mu\text{mol L}^{-1}$ )			
	0-1	1-2	>2	All
Mean richness (number of species)	2.0	1.7	0	1.8
Mean community density (fish/0.1 ha)	444.2	59.8	0	359.1
Mean community biomass (g/0.1 ha)	1924.4	588.6	0	1597.0
Mean Brook Trout density (fish/0.1 ha)	280.8	15.0	0	224.2
Mean Brook Trout biomass (g/0.1 ha)	1384.0	303.3	0	1133.5
Number of streams	38	6	4	48
Percent of streams	79	13	8	100

**Figure 4. Relations between inorganic monomeric Al ( $Al_i$ ) and fish metrics**

The relations between  $Al_i$  concentrations and (A) species richness, (B) total community density, (C) total community biomass, (D) density of Brook Trout, and (E) biomass of Brook Trout from 60 fish surveys in 48 streams (six sites were sampled annually for three years) in the Western Adirondacks that were sampled during summer 2014–2016.



## 5.2 Temporal Variability and Power Analysis

Species richness exhibited the least temporal variability of all 21 metrics but is not an abundance-based metric and is, therefore, of limited utility for assessing temporal changes in headwater streams where fish communities are typically composed of a small number of species. Of the remaining 20 metrics, the temporal variability differed significantly as a result of metric standardization technique (length, area, or effort) and whether metrics were calculated for the entire community or for Brook Trout alone. However, a significant difference was not detected between metrics calculated by density versus biomass or in metrics derived from single-pass versus multi-pass electrofishing surveys. Metrics calculated by reach length had lower mean and maximum CV in all instances compared to those calculated by area. The mean CVs of length- and effort-based metrics were reduced by 12% and 17%, respectively, relative to area-based metrics. The CVs for the 10 Brook Trout population metrics were always higher than those of the 10 comparable community metrics. The mean CV of community metrics was about 12% less relative to Brook Trout metrics. Although temporal variability did not differ significantly between density or biomass metrics, biomass metrics had lower mean CV in seven of the 10 comparable comparisons. No discernable pattern or differences were noted between single-pass and multi-pass metrics although multi-pass metrics yielded a small and statistically insignificant reduction in CV. As a result, the metric that met all of these criteria, the multi-pass estimate of community biomass standardized by reach length, exhibited the least temporal variability (excluding richness).

Notable differences were evident in the power that could be achieved at a fixed level of sampling effort using different metrics. The number of sampling events at all 13 sites (N) needed to detect a 30% change with power of 0.80 ranged from one for species richness to 15 for Brook Trout density by reach area (Table 2). Furthermore, our simulations indicated one metric, the first-pass density of Brook Trout by reach area, could not achieve the desired power with up to 60 sampling events, the maximum considered in the simulation. The power curves of most metrics exhibited an inflection point between an N of four and 10, above which the rate of improvement in effect size that could be detected with power of 0.80 decreased rapidly. As a result, increasing the number of sampling events beyond 15 produced only marginal improvement in the effect size that could be detected using most metrics. A comparison of all metrics indicated that temporal variability was inversely related to power. There was a significant relation between the mean CV and the number of sampling events needed to detect a 30% change with power of 0.80 (Figure 5). Metrics with mean CV < 0.3 required three or fewer sampling events to achieve the desired power while metrics with CV 0.3-0.4 required three-eight sampling events, and metrics with CV > 0.4 required eight or more sampling events.

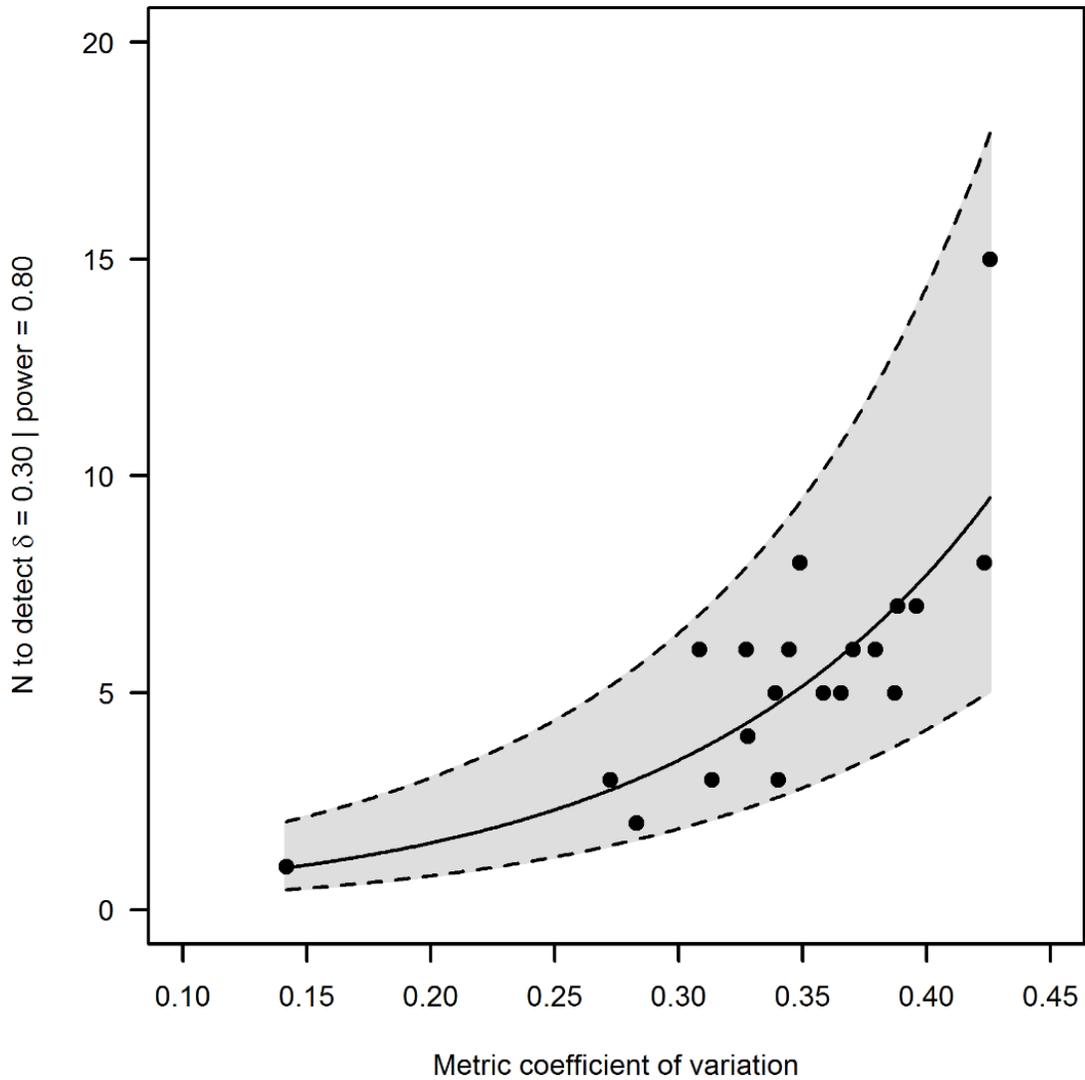
**Table 2. Temporal variability and power of 21 fish metrics**

Mean coefficients of variation for 21 fish metrics from 13 sites sampled annually showing number of sampling events (N) necessary to detect an effect size of 0.30 (30% change) in future monitoring. NA indicates that the effect was not detected at the maximum number of sampling events considered (N = 60).

<b>Metric</b>	<b>Standardization Technique</b>	<b>Units</b>	<b>Range</b>	<b>Mean CV</b>	<b>N to detect <math>\delta = 0.30</math></b>
Community density	Reach area	Fish/0.1 ha	14.8 – 3009.8	0.387	5
Community density	Reach length	Fish/100 m	5.2 – 2356.5	0.340	3
Community biomass	Reach area	Grams/0.1 ha	625.5 – 14,059.8	0.327	6
Community biomass	Reach length	Grams/100 m	219.9 – 7985.2	0.272	3
Community first-pass density	Reach area	Fish/0.1 ha	11.1 – 1617.8	0.396	7
Community first-pass density	Reach length	Fish/100 m	3.9 – 816.1	0.344	6
Community first-pass biomass	Reach area	Grams/0.1 ha	439.1 – 10,143.5	0.349	8
Community first-pass biomass	Reach length	Grams/100 m	158.0 – 1722.4	0.313	3
Community first-pass density	CPUE	Fish/h	14.7 – 889.5	0.283	2
Community first-pass biomass	CPUE	Grams/h	419.2 – 4257.5	0.308	6
Brook Trout density	Reach area	Fish/0.1 ha	14.8 – 1417.2	0.426	15
Brook Trout density	Reach length	Fish/100 m	5.2 – 219.0	0.365	5
Brook Trout biomass	Reach area	Grams/0.1 ha	564.8 – 7044.4	0.379	6
Brook Trout biomass	Reach length	Grams/100 m	167.4 – 2369.6	0.339	5
Brook Trout first-pass density	Reach area	Fish/0.1 ha	11.1 – 923.4	0.425	NA
Brook Trout first-pass density	Reach length	Fish/100 m	3.9 – 155.1	0.358	5
Brook Trout first-pass biomass	Reach area	Grams/0.1 ha	229.0 – 6073.0	0.423	8
Brook Trout first-pass biomass	Reach length	Grams/100 m	118.0 – 1103.8	0.370	6
Brook Trout first-pass density	CPUE	Fish/h	14.7 – 368.8	0.328	4
Brook Trout first-pass biomass	CPUE	Grams/h	267.8 – 4257.5	0.388	7
Species richness	None	No. species	1.0 – 9.0	0.142	1

**Figure 5. Metric variability, sample size, and power**

Relation between the mean coefficient of variation (CV) and sample size (number of sampling events, N) needed to detect a 30% change with a power of 0.80 for 20 fish metrics (the first-pass density of Brook Trout by reach area metric is not plotted because it could not achieve the desired power with up to 60 sampling events). Black line is the mean predicted number of sampling events at the 13 sites required to detect 30% change with power of 0.80.



### 5.3 Study Implications

This report addresses two critical knowledge gaps in our understanding of the effects of acidification on headwater streams and the ability to monitor those streams. First is that fish assemblages in headwater streams of New York State are understudied and little quantitative information is available on their conditions prior to the onset of acidification. This lack of information has impeded efforts to determine the effects of acidification and to set appropriate goals for recovery. Second, fish assemblages in headwater streams are highly variable over time due to the extreme environmental fluctuations (e.g. desiccation, floods, ice, etc.) characteristic of this habitat type. Therefore, detecting change over time, or progress towards a recovery target, with adequate statistical power is difficult and little is known about which metrics or standardization techniques are best suited for this task.

The first problem was addressed by applying existing knowledge of acid-base chemistry toxicity thresholds (Baldigo et al., 2007) to an assessment of water chemistry and fish assemblages at 48 streams to identify unimpacted, slightly impacted, and severely impacted fish assemblages. During summer surveys,  $Al_i$  concentrations were greater than 1.0 and 2.0  $\mu\text{mol L}^{-1}$  in 10 (21%) and four (8%) of the streams sampled, respectively. Total richness, density, biomass, and the density and biomass of Brook Trout populations all decreased between the  $<1.0 \mu\text{mol L}^{-1}$ ,  $1.0\text{-}2.0 \mu\text{mol L}^{-1}$ , and the  $>2.0 \mu\text{mol L}^{-1}$   $Al_i$  stream classes (i.e., as  $Al_i$  increased). Given existing knowledge of  $Al_i$  toxicity thresholds, fish assemblages of streams in the  $Al_i <1.0 \mu\text{mol L}^{-1}$  stream class should represent the unimpacted condition in which toxicity is not shaping the distribution or abundance of species present. Thus, if it is assumed space-for-time substitution is valid (Pickett, 1989), the current richness, density, and biomass values for streams of the  $<1.0 \mu\text{mol L}^{-1}$   $Al_i$  class may be reasonable estimates of the pre-acidification condition of fish assemblages. These benchmarks for species richness, density, and biomass of 2.0 species, 444.2 fish/0.1 ha, and 1924.4 g/0.1 ha, respectively, and density and biomass of Brook Trout populations of 280.8 fish/0.1 ha and 1384.0 g/0.1 ha may serve as approximate recovery targets for headwater streams where acidification and toxicity continue to adversely affect fish assemblages.

With greater knowledge of biological recovery targets in hand, the next step was to develop a strategy to effectively monitor for changes in these highly variable communities. This was achieved through an assessment of temporal variability and power analysis of 21 candidate fish metrics that identified immense differences in the sample size necessary to achieve adequate power for the various metrics. For example, the simulation indicated only one sampling event at all 13 sites (i.e., 13 stream surveys)

would be necessary to detect a 30% change from our existing dataset with power of 0.80 using the species richness metric compared to 15 sampling events (an additional 182 stream surveys) using the Brook Trout density by area metric. Considering a typical electrofishing survey might require a team of four to seven individuals between four and eight hours to complete, the difference in effort required to achieve the same statistical power with these two metrics could require substantially more resources and delay management decisions by more than 10 years.

The results indicated metrics calculated for entire fish communities that were standardized by reach length or sampling effort generally had the lowest temporal variability, and therefore, the greatest statistical power. Although effort-based and other single-pass metrics performed relatively well in our simulation, assessments of variability and power do not account for metric accuracy. Effort-based or single-pass metrics cannot assess capture probability and do not produce population estimates with known levels of error—and thus, may not be ideal for monitoring progress towards recovery targets. Therefore, multi-pass surveys of entire fish communities standardized by reach length may be the most practical and effective way to monitor change in fish communities at fixed locations over time. However, comparisons between streams are more appropriately made using metrics standardized by area or effort to account for differences in stream size (e.g., width, discharge, drainage area, etc.). Finally, although the focus was on detecting an effect size of 30%, simulations indicated that an effect size of 20% could be achieved for most metrics with considerably more sampling effort, whereas an effect size of 10% could be achieved only for the species richness metric, regardless of the number of sampling events (George et al., 2019). This suggests that metrics of fish abundance or biomass may vary too much to consistently detect a change of less than 20% in headwater streams, and that future monitoring efforts should aim to identify an effect size of 20–30%.

## 6 Conclusions

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The richness, abundance, and biomass of fish assemblages in headwater streams of the western Adirondacks were negatively related to summer  $\text{Al}_i$  concentrations. The condition of fish assemblages in 38 streams with summer  $\text{Al}_i$  concentrations less than  $1.0 \mu\text{mol L}^{-1}$  were used to identify recovery targets for streams adversely affected by acidification. In streams with low  $\text{Al}_i$  concentrations, species richness, density, and biomass averaged 2.0 species, 444.2 fish/0.1 ha, and 1924.4 g/0.1 ha, respectively, and the density and biomass of Brook Trout populations averaged 280.8 fish/0.1 ha and 1384.0 g/0.1 ha. Because these measurements represented streams with a wide range in chemistry that extended to levels that could be considered unimpacted, these values provide a reasonable approximation of the condition of fish communities prior to anthropogenic acidification and can be used as targets for monitoring and assessing future recovery of fish assemblages in streams of the region.

The statistical power to detect change differed strongly between 21 fish metrics considered in this study. Thus, the ability to identify a change in resource condition and the resources needed to detect that change strongly depend on selecting the appropriate metric. Analysis indicated that greater statistical power could be obtained from metrics based on entire fish communities and metrics standardized by reach length or effort. Given the variability observed in our dataset, a reasonable monitoring goal would aim to detect a change (effect size) of 30%, although a 20% change could also be detected using most metrics with a substantial increase in sampling effort.

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