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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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The Bear Brook Watershed in Maine: Multi-decadal whole-watershed experimental acidification

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Abstract

The Bear Brook Watershed in Maine (BBWM) is a long-term research site established to study the response of forest ecosystem function to environmental disturbances of chronic acidic deposition and ecosystem nitrogen enrichment. Starting in 1989, the West Bear (treated) watershed received bimonthly applications of ammonium sulfate [$(NH_4)_2SO_4$] fertilizer from above the canopy, whereas East Bear (reference) received ambient deposition. The treatments were stopped in 2016, marking the beginning of the recovery phase. Research at the site has focused on soils, streams, and vegetation. Here, we describe data collected over three decades at the BBWM—input and stream output nutrient fluxes, quantitative soil pits and soil chemistry, and soil temperature and moisture.

KEYWORDS
atmospheric deposition, biogeochemistry, experimental acidification, forest soils, nutrient budgets, quantitative soil pits, streams, temperate forests

1 | DATASET NAME

The Bear Brook Watershed in Maine.

2 | RESEARCH SITE

The Bear Brook Watershed in Maine (BBWM) was established in 1986 to investigate ecosystem response to experimental elevated acidic deposition. Research from this site has provided insights on vegetation (Elvir et al., 2010), streamwater (Fernandez et al., 2003; Navrátil et al., 2010; Patel, Fernandez, Nelson, Malcomb, & Norton, 2020), and soil chemistry (Patel et al., 2019; Patel & Fernandez, 2018; SanClements et al., 2010; Wang & Fernandez, 1999), and soil microbial function (Tatariw et al., 2018) during the 27 years of this experimental manipulation. More information on this research site is in Norton and Fernandez (1999) and Fernandez and Norton (2010), as well as the list of publications at https://umaine.edu/bbwm/.

2.1 | Site description

The BBWM is in eastern Maine, USA (44°52'N, 68°06'W, Figure 1) at an elevation of 210–475 m. The site is in the temperate climate zone, with average annual air temperature (2005–2014) of 5.6°C (Patel

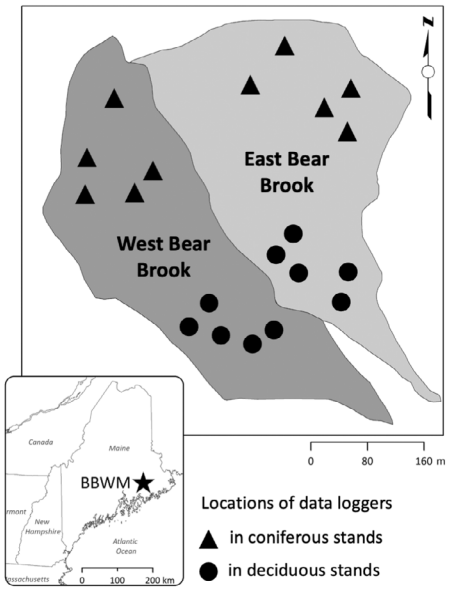

FIGURE 1 Location and layout of the Bear Brook Watershed in Maine. East Bear is the reference watershed, receiving ambient deposition. West Bear is the treated watershed, receiving experimentally elevated N + S deposition plus ambient deposition. The two watersheds are drained by first-order streams, and the cluster plots represent soil sampling locations

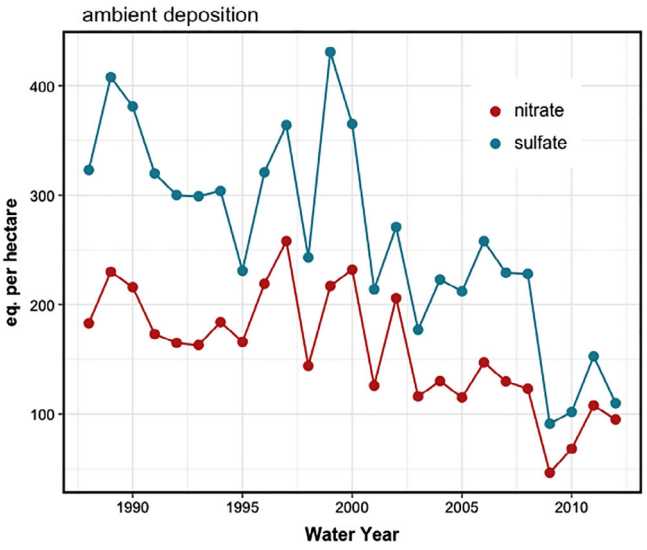

FIGURE 2 Annual ambient nitrate and sulfate input fluxes (wet deposition)

et al., 2018a, 2018b), and average annual precipitation (2005–2014) of 140 cm. The site consists of two paired watersheds, the reference East Bear (EB, 11.0 ha) and the manipulated West Bear (WB, 10.3 ha). Both watersheds are drained by first-order streams. Soils are coarse-loamy, mixed, frigid Typic and Aquic Haplorthods developed in glacial till. Bedrock consists dominantly of low-grade metasedimentary quartzite, phyllite, and calc-silicate gneiss, and minor granite dikes (Norton et al., 1999; SanClements et al., 2010). Vegetation is similar in both watersheds. The lower elevations are dominated by hardwood species, primarily *Fagus grandifolia* Ehrh. (American beech), *Acer saccharum* Marsh. (sugar maple), *Acer rubrum* L. (red maple), and *Betula alleghaniensis* Britt. (yellow birch), whereas softwood species, *Picea rubens* Sarg. (red spruce) and *Abies balsamea* L. (balsam fir) dominate the higher elevations (Wang & Fernandez, 1999). The research site is thus divided into four compartments by N + S treatment and, de facto, forest type—East Bear hardwood, East Bear softwood, West Bear hardwood, and West Bear softwood. Five cluster plots (10 × 15 m) have been established in each compartment, which are the basis of the soil sampling design at the site.

2.2 | Experimental manipulations

The reference EB watershed received ambient atmospheric deposition throughout the project (Figure 2). From November 1989 to October 2016, the WB watershed was treated with bimonthly applications of ammonium sulfate [$(NH_4)_2SO_4$] fertilizer from above the canopy, at a rate of 1800 eq ha^{-1} $year^{-1}$ (28.8 kg S ha^{-1} $year^{-1}$ and 25.2 kg N ha^{-1} $year^{-1}$). October 2016 was the beginning of the recovery phase; current research at the site focuses on the response of the treated system to the sudden loss of experimentally elevated N + S deposition.

3 | METHODS

3.1 | Atmospheric deposition and stream chemistry

3.1.1 | Atmospheric deposition (1989–2012)

Wet-only precipitation was collected using AeroChem Metrics™ (Bushnell, FL) precipitation collectors (Navrátil et al., 2010; Norton et al., 1999). From 1989 to 2000, samples were collected weekly. From 2000 to 2012, sampling frequency was reduced, and samples were collected biweekly or monthly, and during/after selected hydrologic events. Systematic precipitation records at the site are available only until 2012. Precipitation samples were analysed for chemistry at the University of Maine Sawyer Environmental Research Center; the list of analytes measured is in Table 1. Quality checks for precision and accuracy were performed with each run. Analytical runs were accepted only when the accuracy was 5%–10% or less, depending on the analyte (Appendix A). We used measured precipitation volume/area (weekly or longer if no precipitation), and interpolated values between collections to develop annual or monthly deposition fluxes (Figure 2). Dry deposition was not measured at the site, so we use reported estimates of annual dry deposition from the CASTNET Howland station (HOW132), located ~60 km northwest of our site (CASTNET, 2018).

3.1.2 | Stream discharge (1989–2016)

Stream discharge was recorded for both streams, using stainless steel V-notch weirs set in concrete stilling basins (weir elevation 280 m).

TABLE 1 List of analytes measured from stream and soil samples

Wet deposition analytes			
Ca	Mg	K	Na
NH_4	NO_3	SO_4	Cl
pH			
Stream analytes			
Ca	Mg	Na	K
NH_4	NO_3	DOC	DIC
SO_4	Cl	HCO_3 (calculated)	Si
Total Al	Organic Al	pH	ANC
Specific conductance	Total N	Total P	
Soil analytes			
NH_4Cl-extracted analytes			
Ca	Mg	Na	K
Al	Mn	Zn	Pb
Fe			
KCl-extracted analytes			
NH_4	NO_3	Exch. H	Exch. Al
Exch. acidity			
Other soil measurements			
SO_4—S	pH	Total P	Total C
Total N	soil organic matter (loss-on-ignition)		

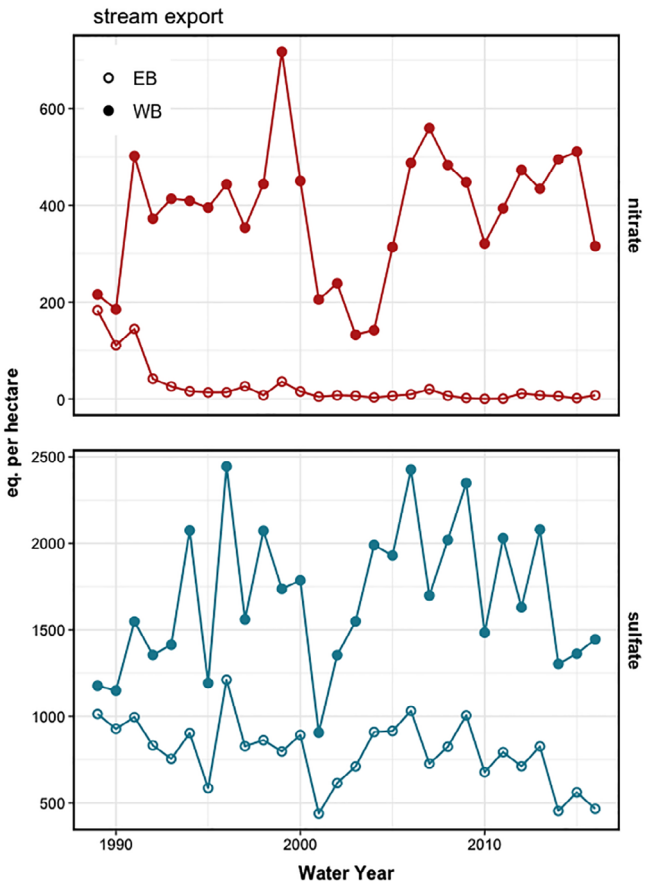

FIGURE 3 Annual nitrate and sulfate output (stream) fluxes for the two watersheds. EB, East Bear (reference); WB, West Bear (treated)

The U.S. Geological Survey (USGS) designed and oversaw installation of the two weirs and maintained the weirs until 2012 (WB) and 2016 (EB). Data were recorded at 5-min intervals with pressure transducers and a redundant float system and uploaded to the USGS website. Streamflow records are available for 1988–2016 for EB and 1988–2012 for WB. All streamflow measurements reported here ceased in 2016.

3.1.3 | Stream chemistry (1989–2016)

Stream samples from both EB and WB streams were collected as grab samples and using ISCO™ (Lincoln, NE) automated samplers during hydrologic events (e.g., during snowmelt and rain events) (Navrátil et al., 2010; Norton et al., 1999). Stream samples were collected concurrently with the precipitation samples—weekly and during high stream-flow events from 1989 to 2000, and biweekly or monthly and during selected hydrologic events from 2000 to 2012. Stream samples were analysed for chemistry at the University of Maine Sawyer Environmental Research Center; the list of analytes measured is in Table 1. Quality checks for precision and accuracy were performed with each run. Analytical runs were accepted only when the accuracy was 5%–10% or less, depending on the analyte (Appendix A). We used streamflow and stream chemistry data, interpolated between collections, to develop monthly and annual stream fluxes (Figure 3). Detailed methods on sampling and analysis are in Kahl et al., 1999 and Norton et al., 2010.

3.2 | Soils—quantitative pits (1998–2013)

Replicate quantitative soil pedons were sampled in the four compartments at BBWM (i.e., EB hardwoods, EB softwoods, WB hardwoods, and WB softwoods) during 1998, 2006, 2010, and 2012–13. The 1998 and 2010 campaigns included quantification of both soil physical and chemical properties; the 2006 and 2012–13 campaigns included only chemical analyses.

The sampling design consisted of 40 quantitative pedons excavated to the bottom of the solum using a 71 cm × 71 cm frame. All O-horizon soil to the top of the underlying mineral soil within the frame was collected. The E-horizon, where present, was excluded from sampling due to its thin, inconsistent presence, and limited chemical reactivity. The mineral soil was quantitatively excavated at depth increments of 0–5, 5–25, and 25 cm to the top of the C-horizon. Where possible, a grab sample of the upper C-horizon was collected.

A list of analytes measured from the soil pits is in Table 1, and acceptable variability for the analytes is reported in Appendix B. Additional details on sampling, processing, and laboratory analysis are in Fernandez et al., 2003 and SanClements et al., 2010.

3.3 | Soil temperature (2001–2015) and moisture (2003–2016)

Air and soil temperature were measured from 2001 to 2015 at three soil depths-surface (organic soil), and 10 and 25 cm in the mineral soil, in both watersheds, and in both the hardwood and softwood forest types. Temperature measurements were recorded every 3 hr using Onset HOBO sensors (Onset Computer Corporation, Bourne, MA, USA), and processed to calculate daily and monthly mean temperatures. Soil moisture measurements are available from 2003 to 2016. Soil moisture was recorded every 3 hr at 10 and 25 cm depths using HOBO™ Micro Station data loggers equipped with 10HS Smart Sensors (Onset Computer Corporation, Bourne, MA, USA). A few moisture loggers were also installed vertically, to integrate moisture content across the top 10 cm. We calculated daily, monthly, and annual mean soil moisture. Instrument information, including sensor accuracy, is reported in Appendix C, and additional processing details are in Fernandez et al., 2007 and Patel et al., 2018a.

4 | APPLICATIONS OF THESE DATA

Long-term watershed studies are a unique opportunity to explore complex ecological processes, and the work at BBWM has provided insights into terrestrial and freshwater nutrient cycling. The data described here have allowed us to identify drivers of chronic and episodic stream acidification (Laudon & Norton, 2010; Navrátil et al., 2010) and recovery (Patel et al., 2020). The strong linkage in streams between particulate and dissolved P and leached Al indicated that P in streams is controlled by desorption of PO_4 from acidic soils, concurrently with Al desorption and dissolution of secondary $Al(OH)_3$ in the soil, followed by re-precipitation of ionic Al and re-adsorption of PO_4 (Roy et al., 1999). Temporal changes in soil chemistry are critical to understanding stream function, as the balance between anions and base cations influences downstream chemistry and acidification (Fernandez et al., 2003; SanClements et al., 2010). Ecosystem budgets have offered insights on nutrient retention in N/S-limited vs. enriched systems, as well as relatively uncommon empirical data regarding whole forested watershed function on a decadal timescale to elucidate short and long-term ecosystem processes (Fernandez et al., 2010; Patel et al., 2019). The long-term soil temperature and moisture data offer evidence of the importance of forest composition in driving soil properties (Fernandez et al., 2007; Patel et al., 2018a). These records also provide important empirical data on the temporal variability and trajectory of variables increasingly critical in a time of accelerating environmental change, which can drive the modelling used to address those applications to socio-ecological systems affected by these changes. We suggest that the data described here will be of use to other researchers investigating ecosystem acidification and recovery, terrestrial-aquatic linkages, a changing climate and other long-term ecosystem processes.

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DATASET CONTRIBUTORS

In addition to the authors, numerous undergraduate and graduate students have contributed to the research at this site over the years. Mike Handley, John Cangelosi, Ken Johnson, Phil Ruck, Richard Dill, and John Schofield (deceased) provided assistance in the laboratory and field, and with data handling. Aria Amirbahman, T. A. Haines, J.S. Kahl, Jean MacRae, Tsutomu Ohno, Lindsay Rustad, and Kevin Simon were co-investigators during periods of this project. The authors welcome collaborations—potential collaborators are encouraged to contact the corresponding authors.

DATA AVAILABILITY STATEMENT

The datasets described here are hosted at the Environmental Data Initiative (EDI, https://environmentaldatainitiative.org/). All existing datasets from this site can be accessed by searching for the keywords "BBWM" or "Bear Brook." Research is ongoing at the site, and the datasets will be periodically updated on EDI.

- Long-term atmospheric deposition chemistry 1987–2012 (Patel et al., 2020a).
- Long-term stream chemistry 1986–2016 (Patel et al., 2020b).

- Soil quantitative pit chemistry 1998–2010 (Patel, et al., 2020c).
- Soil moisture record 2003–2016 (Patel et al., 2020d).).
- Long-term soil temperature 2001–2016 (Patel et al., 2020e).

Additional datasets from BBWM are hosted in other repositories:

- The daily and monthly air/soil temperature datasets are hosted at PANGAEA (Patel et al., 2018b) and are described in greater detail at Patel et al. (2018a).
- Continuous stream discharge data are hosted on the USGS website (USGS 01022294, https://waterdata.usgs.gov/nwis/uv/?01022294 and USGS 01022295, https://waterdata.usgs.gov/usa/nwis/uv?01022295).

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APPENDIX A.

TABLE A1 Technical quality assurance goals for precipitation/stream water chemistry analyses

Analyte	Holding time[a]	Method[b]	Precision	Accuracy
Ca	6 months	Ion chromatography	±10%	±10%
Mg	6 months	Ion chromatography	±10%	±10%
Na	6 months	Ion chromatography	±10%	±10%
K	6 months	Ion chromatography	±10%	±10%
NO_3	28 days	Ion chromatography	±5%	±4%
DOC	28 days	IR analyser	±5%	±5%
DIC	28 days	IR analyser	±5%	±5%
SO_4	28 days	Ion chromatography	±5%	±4%
Cl	28 days	ION chromatography	±5%	±4%
Si	28 days	Autoanalyser	±5%	±4%
Al, total dissolved	6 months	ICP-MS	±10%	±5%
pH	48 hours	Electrode	±0.075 (≤5.74) ±0.15 (>5.75)	±0.025 (≤5.74) ±0.05 (>5.75)
ANC	28 days	Gran titration	±5%	±4%
Specific conductance	28 days	Electrode	±2%	±2%
Apparent colour	48 hours	Spectrophotometry	±10%	±5%
Total N	28 days	Automated colorimetry	±5%	±5%
Total P	28 days	Manual colorimetry	±5%	±5%

[a]Holding time is the maximum time allowed from sample collection to analysis.
[b]If different methods were used over the duration of the study, the most recent method used is reported here. The full record of methods used is available in the dataset metadata.

APPENDIX B.

TABLE A2 Technical quality assurance goals for soil chemistry analyses

	Method	Precision	Accuracy
Ca	ICP	±10%	±10%
Mg	ICP	±10%	±10%
Na	ICP	±15%	±15%
K	ICP	±20%	±20%
Al	ICP	±20%	±20%
Zn	ICP	±15%	±10%
Mn	ICP	±10%	±10%
Pb	ICP	±10%	±10%
Fe	ICP	±10%	±10%
Soil pH	Electrode	±10%	±10%
Total C	Combustion	±10%	±10%
Total N	Combustion	±5%	±10%
Total P	ICP	±15%	±15%

APPENDIX C.

TABLE A3 Technical specifications for instrumentation and sensors used at the site

	Instrumentation	Manufacturer	Accuracy objective
Stream discharge	stainless steel V-notch weirs	(installed by USGS)	±2.3%
Soil temperature	TMC1-HD and TMC6-HD Temperature Sensors	Onset Computer Corporation, Bourne, MA, USA	±0.2 °C (>0 °C) ±0.9 °C (0 to −30°C)
Soil moisture	S-SMC-M005 Soil Moisture Smart Sensors	Onset Computer Corporation, Bourne, MA, USA	±0.031 m^3/m^3 (±3.1%)