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Impact of mild experimental acidification on short term invertebrate drift in a sensitive British Columbia stream

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Abstract

We report daytime drift behavior of lotic macroinvertebrates following short term (12 h) additions of HCl or HCl plus $AlCl_3$ to a circumneutral softwater (alkalinity ca. 100 μeq l^{-1}) mountain stream in British Columbia, Canada. Addition of HCl (pH reduced from 7.0 to 5.9) resulted in an overall tripling of invertebrate drift density with rapid (< 1 h) increases in chironomid Diptera and Trichoptera. Small Ephemeroptera also entered the drift at high densities, but were delayed about 6 h. Addition of $AlCl_3$ (0.71 to 0.95 mg l^{-1} total Al^{3+}) in HCl (stream pH reduced to 5.9) resulted in an overall 6-fold increase in invertebrate drift, with rapid increases by Ephemeroptera and delayed responses by chironomids and Trichoptera. These results suggest that the behavior of several macroinvertebrates from low alkalinity, unacidified streams can be altered by simulations of short-term, mild acidic deposition events. Further, the magnitude and timing of entry into the drift varies among taxonomic groups with the presence or absence of low concentrations of aluminum ions.

Introduction

The deposition of acidic atmospheric pollutants of anthropogenic origin has resulted in recent acidification of surface waters in eastern North America and northern Europe. Streams undergoing acidification often suffer rapid pH depressions during rainstorms and/or snowmelt events, accompanied by increases in dissolved aluminum which is mobilized from sediments and soils in the surrounding catchment (Drablos & Tollan, 1980; Driscoll *et al.*, 1983). Both H^+ and Al^{3+} are toxic to many stream invertebrates and vertebrates (e.g. Haines, 1981; Okland & Okland, 1986).

Long term exposures to acidification have been associated with changes in species diversity, composition and abundance in lakes and streams (Drablos & Tollan, 1980; Haines, 1981; Dillon *et al.*, 1984; Burton *et al.*, 1985, Schindler *et al.*, 1985; Schindler, 1988). Physiological acclimation of some organisms (McWilliams, 1980), evolution of tolerance (Swarts *et al.*, 1978), loss of sensitive species or replacement by more resistant forms (Hall *et al.*, 1980; Schindler *et al.*, 1985; Hall & Ide, 1987) probably act to increase the tolerance of exposed communities to both chronic and episodic acidification. Nearly all experimental studies to date have been conducted on these kinds of communities, using streams with histories of strong episodic pH depressions (pH < 5.0) and/or high experimental dose rates (depressions > 2 pH units; Hall *et al.*, 1980, 1982, 1987; Zishke *et al.*, 1983; Burton *et al.*, 1985; Allard & Moreau *et al.*, 1987; Ormerod *et al.*, 1987; but see Hopkins *et al.*, 1989). We hypothesized that macroinvertebrates in streams with histories of relatively mild or no pH depressions are sensitive to very mild pH and aluminum fluctuations.

In this paper, we present data from an experiment on an acid sensitive stream in British Columbia relevant to two questions. First, do stream invertebrates that have experienced little or no previous depression of stream pH alter short term drift patterns following mild pH depressions (pH 7.0 to 5.9)? Second, do mild doses of aluminum (<35% above background concentrations) at pH 5.9 affect drift differently than pH depressions alone?

Study site

Additions of HCl and HCl plus $AlCl_3$, both at stream pH 5.9, were made to lower Mayfly Creek (49° 19′ N, 122° 34′ W) located in the Coast Range Mountains, 315–760 m A.S.L., in the Malcolm Knapp Research Forest of the University of British Columbia, ca. 50 km east of Vancouver, B.C. Mayfly Creek is a high gradient (11%), second order stream in mountainous terrain covered mainly in coniferous forest [dominants: Douglas fir (*Pseudotsuga menzesii*), western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*)]. Podzolic soils in the watershed are thin, acidic (pH < 4), and low in base saturation (Klinka & Lowe, 1975; Valentine & Lavkulich, 1978). Quartz diorite forms the parent material (Roddick, 1965). Annual rainfall is high (> 225 cm) and runoff is rapid (Feller & Kimmins, 1979). Stream discharges in a similarly sized creek nearby (East Creek) exceed 1000 l s^{-1} from October until April, but fall to less than 10 l s^{-1} baseflow during summer months except after storm events. Mayfly Creek temperatures vary annually between −2 and 20 °C and ranged 13–15 °C during the study reported here.

Chemically, streams in this area are characterized by neutral to slightly acidic water (pH 6.5–7.3, Feller & Kimmins, *op. cit.*). Alpine and montane streams in the coastal ranges of Washington and British Columbia are described as very sensitive to anthropogenic acidification, yet have suffered little impact to date (Welch *et al.*, 1986; Sullivan & Samis, 1988). Streams are characterized by low alkalinity, conductivity and buffering capacity (Sullivan & Samis, *op. cit.*). In undisturbed watersheds such as Mayfly Creek (last logging or fire in 1931), conductivity of the water is low (ca. 20 $\mu S\ cm^{-1}$) and concentrations of most major ions (K^+, Ca^{2+}, Mg^+, Na^+, Cl^-) are much less than 2 mg l^{-1} (see Table 1).

Experiments were conducted along a section of riffles 1.5 m wide in lower Mayfly Creek during low flow in late August 1982. During this season many macroinvertebrates are growing rapidly or initiating physiological changes associated with emergence and may be particularly acid sensitive (R. Hall, pers. comm.). The timing of these experiments also mimics potential, mild acidic depositions that may occur with prolonged atmospheric temperature inversions along the coastal mountains during summer (Welch *et al.*, 1986; Sullivan & Samis, 1988). At our site, the stream gradient was relatively low (3%) and the substratum consisted of 3–6 cm gravel.

Materials and methods

To test for the effect of H^+ and Al^{3+} at stream pH 5.9 on macroinvertebrate drift, 0.25 N HCl or $AlCl_3$ in HCl were dripped into Mayfly Creek for approximately 12 h. Sensitivity of invertebrates to these treatments was assayed by the timing and density of drift. Aqueous solutions of reagent grade HCl and hydrated $AlCl_3$ crystals in HCl were prepared using 300 μm filtered Mayfly Creek water. HCl and $AlCl_3$ were chosen because chloride ions at these concentrations would have minimal effects on the biota (Hall *et al.*, 1985, 1987; Bernard, 1985). Dilute solutions were dripped into experimental sections of Mayfly Creek from an 80 L fiberglass tank across the width of a riffle to ensure rapid mixing with stream water. Unreplicated trials were conducted at the same site within one week to minimize differences in stream discharge and invertebrate population size/stage structures between treatments. Logistical considerations precluded simultaneous exposure of the stream to the treatments. Recolonization from natural nighttime drift quickly obscured (<6 h) any effects of disturbance, as measured by benthic and drift samples (Bernard, 1985). Very high stream flows due to storms prevented repetitions of the experiments in subsequent weeks.

Dosing for each experiment occurred on separate days from about 0800 until 2000 Pacific Daylight Time. This timing was adequate for establishment of daytime drift patterns prior to additions and provided sufficient time to detect delays in drift response. A saturated solution of anhydrous $CaCO_3$ in creekwater was slowly dripped into the stream below the experimental section to raise the pH and avoid impacts on downstream biota.

Physical and chemical sampling

In the absence of a gauging station on Mayfly Creek, stream discharge was assessed by a stadium rod driven into the creek bottom. Measurements were made at the beginning and end of each 12 h treatment period for the following: water depth and velocity at each sampling net (model C-2 Ott current meter), water temperature and electrical conductivity (model CDM-3 Radiometer meter). pH was recorded continuously during each treatment run at locations above and within the acidified reach using a grounded Corning combination glass electrode on a Horizon pH meter (5997-20) attached to a Rustrack stripchart recorder. Subgravel pH at the end of the acidified reach was also monitored by vacuuming water samples through a standpipe inserted in the gravel to a depth of 0.5 m.

Grab samples for dissolved Al, Ca, Mg, K, and Na were filtered (0.45 μm Millipore), acidified (2 ml ultrapure HNO_3) and stored at 4 °C in new, acid-washed polyethylene bottles. Samples evaporated to 50 ml were analysed via inductively coupled plasma spectrophotometry. Detection limits were 0.01 mg l^{-1} for Al and K, 0.02 mg l^{-1} for Ca and Mg, and 0.10 mg l^{-1} for Na. During the $AlCl_3$ addition treatment, dissolved monomeric aluminum and added total aluminum were also determined. Monomeric aluminum was extracted in the field from filtered (0.45 μm Millipore) stream water using methyl isobutyl ketone (Barnes, 1975), and extracts were stored at 4 °C in new, acid-washed polyethylene bottles for later analysis via atomic absorption spectroscopy. Total added aluminum concentrations were calculated from Cl-concentrations (unfiltered, colorimetric $HgNO_3$ titrations, APHA, 1984). Alkalinity was measured by titrating 500 ml water samples with certified 0.005 N HCl and plotting the results according to the methods of Gran (Stumm & Morgan, 1970).

Invertebrate sampling

Invertebrate drift was sampled at two locations: at the reference station immediately above the dosing site and at the experimental station 10 m downstream. Drift nets were made of 86 μm mesh Nitex fastened by quick release collars to metal rods inserted into the stream bottom. Nets filtered about 30% of stream flow. Duplicate 45 min samples were collected every 1.2–2 h, starting at least 90 min before dosing began. Small bridges minimized physical disturbance to the benthos. Samples were transferred to plastic bags, preserved in 10% formalin and heat sealed for transport to the laboratory.

Large volumes of fine particulate matter necessitated that samples be seived in the laboratory through a 296 μm mesh filter prior to microscopic enumeration (25 ×). Quantitative corrections for differential laboratory losses among taxonomic categories during the sieving process (Mundie, 1971) could not be made because of the large amount of obscuring organic matter. Based on a laborious analysis of one sample, losses among the various taxonomic categories ranged from 0 to >80%. Only uncorrected values are reported here. Hence, comparisons among taxonomic categories are at best qualitative, whereas quantitative comparisons can be made within a category across times of the day and across treatments.

Because of difficulty classifying very small individuals of nearly all drifting animals, the following categories were devised, with 2 mm being the break point between 'large' and 'small': large and small Ephemeroptera, large and small Chironomidae, large and small Plecoptera, Trichoptera, Hydracarina, Harpactacoida (Copepoda), and *Simulium* (Diptera). These groups comprised >95% of all drifting animals captured. Results have been standardized to an arbitrary 10^4 l sieved through the drift nets.

Results

Physical-chemical conditions

Background concentrations of calcium, magnesium and alkalinity in Mayfly Creek (Table 1) are very close to the theoretical values predicted for waters unaffected by acidic precipitation (National Research Council of Canada, 1981). These data support the argument that the site had been relatively unaffected by acidic precipitation and that the aquatic community was relatively unimpacted by acidification.

After beginning additions of HCl alone or $AlCl_3$ in dilute HCl, downstream pH reached the target value of 5.9 within 30 min. No spikes of acidity occurred below pH 5.75 during the pH-adjustment process. pH at the reference station immediately upstream from the dosing location remained at 6.9–7.0. Test solutions were well-mixed in riffles immediately below dosing locations and no spatial variation in pH could be detected 2 m downstream from the entry points of the solutions. Responses of sub-gravel pH 10 m downstream from the dosing site were delayed about 15 min compared with stream pH. Recovery of sub-gravel pH after we ceased acid addition also was delayed about 15 min. These changes in pH imply rapid purging of the sub-gravel environment by upstream water.

Discharge was nearly constant and near or at base-flow conditions during the week of trials (9–13 l s^{-1}). Mean H^+ concentrations after additions of test solutions began were 1.12×10^{-6} mol l^{-1} (HCl addition) and 1.19×10^{-6} ($AlCl_3$ addition). Adding aluminum chloride increased specific conductivity slightly from 23 μS cm^{-1} to 28 μS cm^{-1} (Table 1). Higher aluminum and Cl^- and lower alkalinity are responses to the addition of acidic HCl and

Table 1. Filtered streamwater chemistry for HCl and $AlCl_3$ addition experiments, sampled in the final 15 min of each 12 h run.

Parameter	HCl addition		HCl + $AlCl_3$ addition	
	Reference	Experimental	Reference	Experimental
pH	7.0	5.9	6.9	5.9
Al^1 (mg l^{-1})	0.31	0.69	0.71	0.95
Al^2 (μg l^{-1})	–	–	62.5	200.0
Ca (mg l^{-1})	2.40	2.61	2.56	2.78
Cl (mg l^{-1})	0.62	3.76	0.62	5.21
Mg (mg l^{-1})	0.32	0.47	0.50	0.48
K (mg l^{-1})	0.13	0.11	0.09	0.11
Na (mg l^{-1})	1.07	1.23	1.24	1.32
alkalinity (as $CaCO_3$, mg l^{-1})	7.11	2.14	6.20	2.00

[1] Total aluminum
[2] Monomeric aluminum

$AlCl_3$ solutions. Cations were elevated slightly under these conditions.

Invertebrate drift

Prior to introducing chemical perturbations, diel invertebrate drift patterns at Mayfly Creek were similar to those recorded many times elsewhere (Waters, 1972). Large Ephemeroptera, large Chironomidae (Diptera), and Hydracarina all exhibited increased drift activity under low light levels. For the remaining groups, drift density remained relatively constant throughout 24 h. At the reference site, background drift density was around 70 animals/10^4 L, with 75% of a drift sample composed of small chironomids. Together, small Mayflies (Ephemeroptera), water mites (Hydracarina), and harpactacoid copepods (Copepoda) comprised an additional 20% of total background drift numbers. However, these latter groups were most prone to being lost during laboratory seiving to remove organic particles and probably are underestimated. Daytime drift densities under non-acidified conditions are summarized as the first plotted points and the reference station points in each panel of Fig. 1.

Upon the addition of HCl to produce pH 5.9 in the stream, Trichoptera and chironomids of all sizes responded immediately with drift densities 4–10× higher than at the reference station (Fig. 1). Small Ephemeroptera showed no initial response to HCl, but quadrupled in the drift after about 6 h of treatment. On the other hand, large Ephemeroptera drifted at the same daytime densities in both experimental and reference reaches (Fig. 1). Occurrences of Hydracarina, harpactacoid copepods, *Simulium*, and all sizes of Plecoptera in the drift were either erratic or invariant with HCl and no treatment effects could be inferred for these taxa (Table 2, Bernard, 1985). In general, mean drift density of all taxa under mild HCl addition was about 3 times higher than at the upstream reference station (Table 2), though composition changed during the 12 h exposure as a result the delayed response of small mayflies.

Drift responses of several Mayfly Creek invertebrates to added $AlCl_3$ (at pH 5.9) were different in their magnitude and timing compared with HCl addition at the same pH. Immediately after aluminum chloride was added, both small and large Ephemeroptera showed sharply elevated (10–15×) drift densities compared with both the reference station and the previous HCl treatment (Fig. 1). Both groups displayed high drift densities throughout the 12 h treatment, though densities of large mayflies tended to be somewhat erratic. Chironomids responded to aluminum additions less rapidly than Ephemeroptera, but en-

Table 2. Mean drift density (animals/10^4 L) for HCl and $AlCl_3$ addition experiments during 12 h of treatment. Standard deviation shown in brackets.

Taxon	HCl addition		$AlCl_3$ addition	
	Reference $n = 20$	Experimental $n = 20$	Reference $n = 18$	Experimental $n = 18$
Ephemeroptera-sm	3.7 (2.7)	14.6 (7.6)	3.3 (1.9)	103.9 (50.2)
Ephemeroptera-lg	0.3 (0.6)	0.8 (1.2)	0.3 (0.6)	5.2 (5.0)
Chironomidae-sm	54.2 (13.7)	148.3 (53.0)	45.0 (14.1)	252.8 (131.1)
Chironomidae-lg	2.0 (1.4)	6.0 (5.1)	2.0 (1.4)	4.7 (4.2)
Trichoptera	2.2 (1.6)	10.4 (7.4)	1.6 (1.2)	5.9 (6.1)
Hydracarina	6.3 (3.8)	10.2 (6.8)	4.3 (2.2)	9.5 (5.7)
Harpactacoida	5.0 (2.3)	8.3 (6.2)	4.2 (3.4)	5.6 (5.0)
Simulium	0.1 (0.2)	0.3 (0.7)	0.5 (1.6)	0.6 (0.9)
Plecoptera-sm	0.8 (0.6)	4.3 (3.0)	0.7 (1.1)	1.4 (1.6)
Plecoptera-lg	0	0.3 (0.7)	0	0

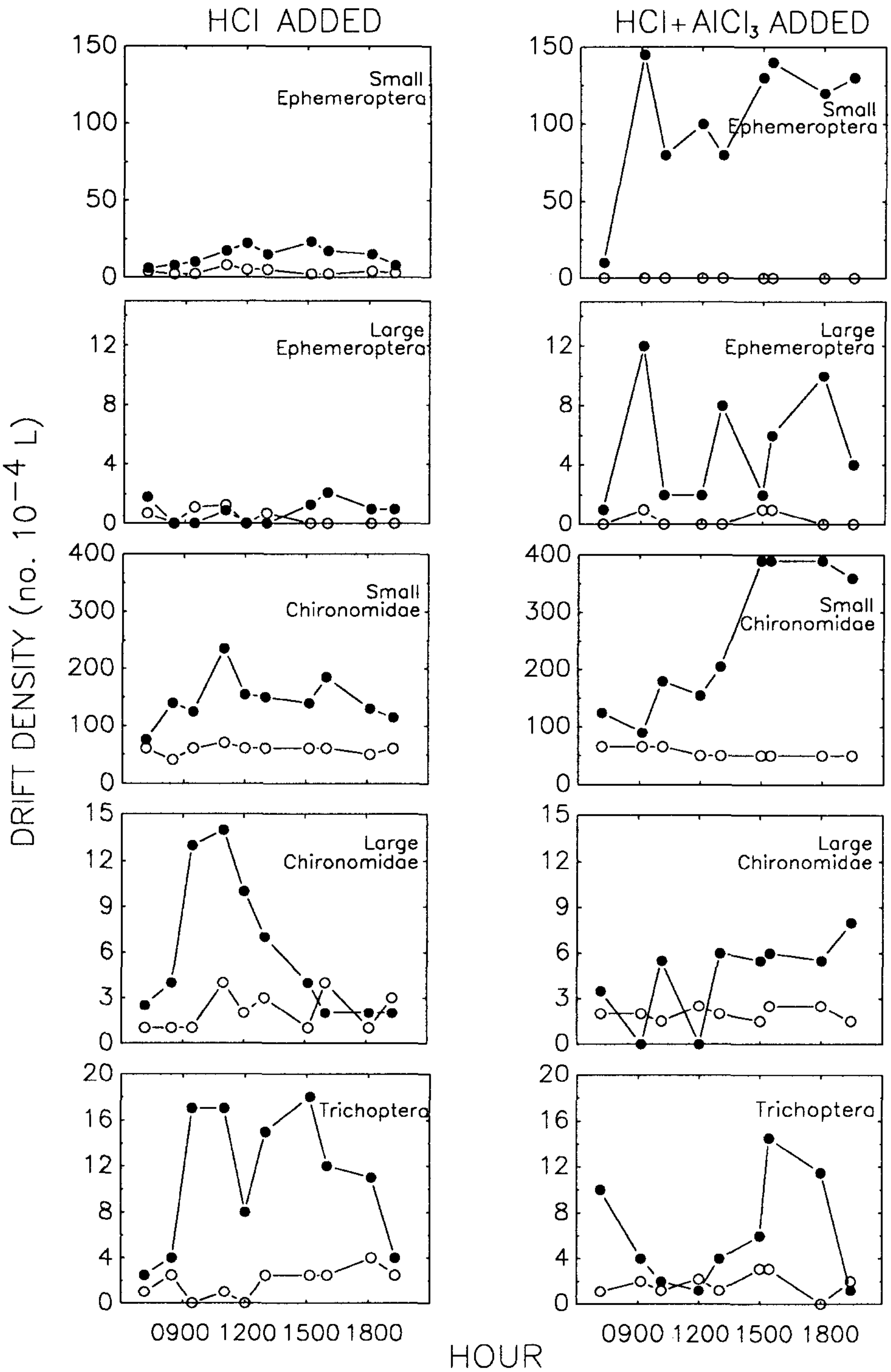

Fig. 1. Drift densities of selected taxonomic categories during experimental 12 h additions of HCl or $AlCl_3$ & HCl in Mayfly Creek at pH 5.9 First plotted points in each panel show pretreatment, morning drift densities in both reference and experimental portions of Mayfly Creek. Hollow circles–reference zone; filled circles–acidified zone.

tered the drift very strongly (4–8 × higher than at the reference station) about 6 h into the treatment. Chironomid densities under $AlCl_3$ treatment were 2–3 × higher than under acid alone. Trichoptera also showed higher drift rates (3–5 × reference station values) during aluminum addition, but tended to be delayed several hours in their responses (Fig. 1). In contrast, Trichoptera had shown rapid and larger (5–7 × reference station) initial responses to HCl alone. Hydracarina were unresponsive to aluminum additions, just as they had been to acid. Harpactacoid copepods, *Simulium*, and stoneflies (Plecoptera) showed no consistent changes from pre-$AlCl_3$ drift densities. Their occurrences in drift nets tended to be infrequent and erratic and are not shown.

In general, mean drift density of all animals under aluminum chloride treatment in Mayfly Creek was about 6 times higher than in the reference section of the stream and more than twice that at the same pH during HCl addition (Table 2). Most of the added effect of aluminum compared with H^+ alone occurred in the last 6 h of treatment, when delayed entry of several groups into the drift was detected. Throughout both treatments, reference station drift densities of the common organisms remained low and nearly constant.

Discussion

Intensive experimental manipulations (e.g., Hall *et al.*, 1980, 1985, 1987; Burton *et al.*, 1985; Allard & Moreau, 1987; Ormerod *et al.*, 1987) demonstrate the effect of acidification and acidic events (pH < 5.5) on the composition and behavior of lotic macroinvertebrates. All these studies employed animals that had been previously exposed to acidification. No experimental stream studies to our knowledge have assessed whether these patterns are also valid under much milder acidic events (near pH 6) in unstressed, circumneutral streams. Further, the relative impacts of hydrogen ions versus toxic metal ions like aluminum near pH 6 in the field are unknown. This study provides some data toward filling this void for threatened, vulnerable streams in western Canada that are currently relatively unimpacted by atmospheric acidification, compared to eastern North America and northern Europe.

The results of our manipulations in Mayfly Creek indicate that:

a) some benthic invertebrates with little or no previous exposure to acidic precipitation are sensitive to half-day exposures of ten-fold higher concentrations of hydrogen and three-fold higher concentrations of monomeric aluminum ions during summer;
b) timing and magnitude of these organisms' entry into the stream drift at pH 5.9 varies with taxonomic group and presence of aluminum ions;
c) stage and size of several common taxonomic groups in late summer seem to have important effects on drift response to hydrogen or aluminum ions at pH 5.9.

These results support the conclusion that very low levels of H^+ and Al^{3+} additions are required to detect adverse effects among previously unexposed macroinvertebrates compared to earlier studies of previously acidified communities. In the least extreme manipulation that we know of, Hall *et al.* (1987) reported no effect on daytime drift rates of a ten-fold increase in H^+ (pH 6.4 to 5.2–5.5) in acidic Norris Brook. Hopkins *et al.* (1989) observed increases in drift of *Baetis* nymphs in experimentally acidified channels in a high altitude Sierra Nevada stream, but pH had been reduced to 5.04. In contrast, we found a tripling of mean total drift densities after mild acidification to pH 5.9, with means of certain groups increasing up to five times. Peak drift densities were up to 10 times higher than at the reference site. As in previous studies which employed more severe pH depression (e.g. Hall *et al.*, 1980, 1985; Allard & Moreau, 1987; Ormerod *et al.*, 1987), we found chironomids, Ephemeroptera and Trichoptera to be sensitive to increases in hydrogen ions. Unlike in more severe manipulations elsewhere, blackflies were unaffected by either mild HCl or $AlCl_3$ in Mayfly Creek.

Six-fold increases in mean total drift density occurred after monomeric aluminum concentration tripled during $AlCl_3$ additions (63 to

200 $\mu g l^{-1}$). Twelve-hour means of sensitive taxa increased 3–30 times, and peak drift densities of these groups were 10–45 times greater than at the reference site. Ephemeroptera were particularly sensitive to aluminum. In general, the same groups that displayed elevated drift rates under HCl at pH 5.9 showed high drift rates under $AlCl_3$ at pH 5.9, but 1.5–10 times higher. Large mayflies, which had shown no clear response to mild H^+ alone, increased under aluminum exposure. Aluminum induced drift rates in Mayfly Creek are comparable to those observed under higher aluminum doses applied to previously stressed streams in eastern North America (Hall *et al.*, 1980, 1985) and Wales (Ormerod *et al.*, 1987).

Harpactacoid copepods, Hydracarina, simulid Diptera and Plecoptera failed to respond to either HCl or $AlCl_3$ at pH 5.9. Many Plecoptera and harpactacoid copepods appear to be insensitive in other studies as well (e.g., Bell & Nebeker, 1969; Bell, 1971; Otto & Svensen, 1983; Mackay & Kersey, 1985). The processes resulting in their apparent tolerance to acid and aluminum are unknown.

Not all sensitive groups responded with the same timing to the two experimental perturbations. Trichopterans, for example, entered the drift immediately upon exposure to HCl, but were delayed by 6 h after exposure to $AlCl_3$ in HCl (as were nearly all other groups). Ephemeroptera were just the reverse: slow in responding to HCl and immediate in responding to $AlCl_3$. Such variations in timing of entry into the drift probably have several nested levels of explanation involving physiological, behavioral and ecological processes, as well as taxonomy. They certainly have strong implications for accurate sampling of drift rates during acidic events. We surmise that very rapid, large pulses of animal drift at the start of treatments (e.g., chironomids to H^+ and Ephemeroptera to Al^{3+}) represent avoidance behavior. Exposed, highly sensitive organisms may be able to escape via drift to more dilute or better buffered conditions downstream. Bernard (1985) supported this hypothesis by showing that rapidly responding mayflies collected in a stream experimentally acidified to pH 5.7 had >95% survival when subsequently held in circumneutral water for 24 h.

Delayed entry into the drift may be caused by gradual erosion of physiological coping mechanisms, slow accumulation of physiologically harmful agents, gradual penetration of refuges (e.g., leaf packs) by deleterious ions, or merely the length of time to reach the stream from deep in the gravel. Species within any one invertebrate category clearly have different abilities with respect to each of these possibilities. Some groups are well-known to have many acid tolerant species [e.g., Trichoptera (Friberg, 1980; Mackay & Kersey, 1985)]. Many of these reside in spatial refuges which may reduce exposure to stressful ions (via sorbtion, restricted water flow, etc.; Allard & Moreau, 1987; Giberson & Hall, 1988). Rapid drift responses by Trichoptera to HCl but slow responses to $AlCl_3$ (and *vice versa* for small Ephemeroptera) may thus represent different behaviors of these ions in various microhabitats, differential sensitivity to H^+ vs. Al^{3+}, or different species' susceptibilities.

Although not essential for our purpose, it is unfortunate that we were unable to make quantitative estimates of drift changes at the species or generic levels. We were able to identify large individuals (Bernard, 1985), but because >98% of all specimens captured in our drift nets were very small, reliable, quantitative counts at high taxonomic resolution were not possible. Species differences in the magnitude and timing of responses to H^+ and Al^{3+} were almost certainly present in Mayfly Creek (Hall *et al.*, 1987; Ormerod *et al.*, 1987).

Finally, the above results have several implications for biomonitoring of streams for the effects of acidification:

1. Because relatively naive benthic organisms as in Mayfly Creek may respond to very mild acid and aluminum pulses, monitoring for acidification should begin at the earliest indication of acidic inputs to poorly buffered streams. Substantial community change may occur during these early phases.
2. If 'threshold concentrations' of H^+ and Al^{3+}

are necessary before detectable benthic responses occur, those concentrations are substantially lower in relatively unimpacted communities than has been estimated for previously exposed communities.

3. Effects of even very mild acid events can occur rapidly (in hours, not days). This result implies that sampling must be initiated quickly after onset of acidic events occur to detect movement of particularly sensitive groups.
4. Drift is potentially a more sensitive indicator of early stages of acidification than benthic densities or presence/absence of selected groups. Behavioral responses such as avoidance drift seem to occur at lower concentrations of deleterious agents than is necessary to produce mortality or to eliminate whole taxa. Sample variability is lower as well, allowing more confidence in the assessment.
5. Ecotoxicological studies prior to detecting acidification can provide important indicators of potentially sensitive species/stages/seasons in which to conduct detailed laboratory assays.

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References

Allard M. & G. Moreau, 1987. Effects of experimental acidification on a lotic macroinvertebrate community. Hydrobiologia 144: 37–49.

APHA, 1984. Standard methods for the examination of water & wastewater. American Public Health Association, New York.

Barnes, R. B., 1975. The determination of specific forms of aluminum in natural waters. Chem. Geol. 15: 177–191.

Bell, H. L., 1971. Effect of low pH on the survival and emergence of aquatic insects. Wat. Res. 5: 313–319.

Bell, H. L. & A. V. Nebeker, 1969. Preliminary studies on the tolerance of aquatic insects to low pH. J. Kansas Entomol. Soc. 42: 230–236.

Bernard, D. P., 1985. Impact of stream acidification on invertebrates: drift responses to *in situ* experiments augmenting aluminum ion concentrations. M. Sc. Thesis. University of British Columbia.

Burton, T. M., R. M. Sanford & J. W. Allen, 1985. Acidification effects on stream biota and organic matter processing. Can. J. Fish. aquat. Sci. 42: 669–675.

Dillon, P. J., N. D. Yan & H. H. Harvey, 1984. Acidic deposition: effects on aquatic ecosystems. CRC Crit. Rev. Envir. Control 13: 167.

Drablos, D. & A. Tollan (eds.), 1980. Ecological impact of acid precipitation. SNSF, Oslo.

Driscoll, C. T., J. P. Baker, J. J. Bisogni & C. L. Schofield, 1983. Aluminum speciation and equilibria in dilute acidic surface water of the Adirondack region of New York state. In: Bricker, O. P. (ed.). Geologic aspects of acid rain. Ann Arbor Science, Ann Arbor, pp. 55–75.

Feller, M. & J. P. Kimmins, 1979. Chemical characteristics of small streams near Haney in southwestern British Columbia. Water Resource Res. 15: 247–258.

Friberg, F., C. Otto & B. S. Svenson, 1980. Effects of acidification on the dynamics of allochthonous leaf material and benthic invertebrate communities in running waters. In: Drablos, D. & A. Tollan (eds.). Ecological impact of acid precipitation. SNSF, Oslo, pp. 304–305.

Giberson, D. J. & R. J. Hall, 1988. Seasonal variation in faunal distribution within the sediments of a Canadian shield stream, with emphasis on responses to spring floods. Can. J. Fish. aquat. Sci. 45: 1994–2002.

Haines, R. A., 1981. Acidic precipitation and its consequences for aquatic ecosystems: a review. Trans. Am. Fish. Soc. 110: 669–707.

Hall, R. J., C. T. Driscoll & G. E. Likens, 1987. Importance of hydrogen ions and aluminum regulating the structure and function of stream ecosystems: an experimental test. Freshwat. Biol. 18: 17–43.

Hall, R. J., C. T. Driscoll, G. E. Likens & J. M. Pratt, 1985. Physical, chemical and biological consequences of episodic aluminum additions to a stream ecosystem. Limnol. Oceanogr. 30: 212–220.

Hall, R. J. & F. P. Ide, 1987. Evidence of acidification effects on stream insect communities in central Ontario between 1937 & 1985. Can. J. Fish. aquat. Sci. 44: 1652–1657.

Hall, R. J., G. E. Likens, S. B. Fiance & G. R. Hendry, 1980. Experimental acidification of a stream in the Hubbard Brook Experimental Forest, New Hampshire. Ecology 61: 976–989.

Hall, R. J., J. M. Pratt & G. E. Likens, 1982. Effects of experimental acidification on macroinvertebrate drift density in a mountain stream. Wat. Air Soil Pollut. 18: 273–287.

Hopkins, P. S., K. W. Kratz & S. D. Cooper, 1989. Effects of an experimental acid pulse on invertebrates in a high altitude Sierra Nevada stream. Hydrobiol. 171: 45–58.

Klinka, K. & L. E. Lowe, 1975. Organic constituents of forest humus layers in the Coastal Western Hemlock biogeoclimatic zone of British Columbia in relation to forest ecosystems. 1. Proximate analysis. B.C. Forest Serv., Victoria. Res. Note 74. 16 pp.

Mackay, R. J. & K. Kersey, 1985. A preliminary study of aquatic insect communities in acid streams near Dorset, Ontario. Hydrobiologia 122: 3–11.

McWilliams, P., D. Brown, G. Howells & W. Poole, 1980. Physiology of fish in acid waters. In: Drablos, D. & A. Tollan (eds.). Ecological impact of acid precipitation. SNSF, Oslo, pp. 282–283.

Mundie, J. H., 1971. Sampling benthos and substrate materials down to 50 microns in size, in shallow streams. J. Fish. Res. Bd. Can. 28: 849–860.

National Research Council of Canada, 1981. Acidification in the Canadian aquatic environment: scientific criteria for assessing the effects of acidic deposition in aquatic ecosystems. Environmental Secretariat, NRCC, Ottawa. Publ. No. 18475.

Okland, J. & K. A. Okland, 1986. Effects of acid deposition on benthic animals in lakes and streams. Experimentia 42: 471–486.

Ormerod, S. J., P. Boole, C. P. McCahon, N. S. Weatherley, D. Pascoe & R. W. Edwards, 1987. Short-term experimental acidification of a Welsh stream: comparing the biological effects of hydrogen ions and aluminum. Freshwat. Biol. 17: 341–356.

Otto, C. & B. J. Svenson, 1983. Properties of acid brown water streams in south Sweden. Arch. Hydrobiol. 99: 15–36.

Roddick, J. A., 1965. Vancouver, North Coquitlam and Pitt Lake map areas, British Columbia: with special emphasis on the evolution of the plutonic rocks. Geol. Survey Canada, Mem. 335. 276 pp.

Schindler, D. W., 1988. Effects of acid-rain on fresh-water ecosystems. Science 239: 149–157.

Schindler D. W., K. H. Mills, D. F. Malley, D. L. Findlay, J. A. Shearer, I. J. Davis, M. A. Turner, G. A. Linsey & D. R. Cruikshank, 1985. Long-term ecosystem stress: the effect of years of experimental acidification on a small lake. Science 228: 1395–1401.

Stumm, W. & J. J. Morgan, 1970. Aquatic chemistry. Wiley Interscience, New York.

Sullivan, M. A. & S. C. Samis, 1988. Assessment of acidification potential of selected Lower Mainland and Vancouver Island, British Columbia streams. Can. Tech. Rep. Fish. Aquat. Sci. No. 1599.

Swarts, F. A., W. A. Dunstan & J. E. Wright, 1978. Genetic and environmental factors involved in increased resistance of brook trout to sulfuric acid solutions and mild acid polluted waters. Trans. Am. Fish. Soc. 107: 651–677.

Valentine, K. W. G. & L. M. Lavkulich, 1978. The soil orders of British Columbia. In: Valentine, K. W. G., P. N. Sprout, T. E. Baker & L. M. Lavkulich (eds.). The soil landscape of British Columbia. B.C. Ministry Envir., Victoria, B.C., pp. 67–95.

Waters, T. F., 1972. The drift of stream insects. Ann. Rev. Ent. 17: 253–272.

Welch, E. B., D. E. Spyridakis & T. Smayda, 1986. Temporal chemical variability in acid sensitive high elevation lakes. Wat. Air Soil Pollut. 31: 35–44.

Zischke, J. A., F. W. Arthur, K. J. Nordie, R. O. Hermanutz, D. A. Standen & T. P. Henry, 1983. Acidification effects on macroinvertebrates and fathead minnows (*Pimephales promelas*) in outdoor experimental channels. Wat. Res. 17: 47–63.