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EVALUATION OF EPISODIC ACIDIFICATION AND AMPHIBIAN DECLINES IN THE ROCKY MOUNTAINS[1]

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Abstract. We define criteria for documenting episodic acidification of amphibian breeding habitats and examine whether episodic acidification is responsible for observed declines of amphibian populations in the Rocky Mountains. Anthropogenic episodic acidification, caused by atmospheric deposition of sulfate and nitrate, occurs when the concentration of acid anions increases relative to the concentration of base cations, resulting in a decrease in acid-neutralizing capacity (ANC). However, because several natural processes can also depress ANC, monitoring pH and ANC alone cannot provide evidence that episodic acidification of amphibian habitats is anthropogenic. We examined published data on water chemistry from central Colorado and southern Wyoming for evidence of episodic acidification, and we also compared original water chemistry data to observations of amphibian breeding phenology at three sites in northern Colorado. There is limited evidence that anthropogenic episodic acidification may occur in high-elevation habitats in the Rocky Mountains, but there is no evidence that episodic acidification has led to acidic conditions (ANC <0) or that amphibian embryos are present during the initial phase of snowmelt when episodic acidification might occur. The declines of some amphibian species in the Rocky Mountains are more likely due either to natural or anthropogenic factors other than acidic deposition.

Key words: acid-neutralizing capacity; acidification; Ambystoma tigrinum; *amphibians*; Bufo boreas; *Colorado; declining amphibians; episodic acidification*; Pseudacris triseriata; Rana sylvatica; *snowmelt; Wyoming.*

INTRODUCTION

Declines of common, widespread species of amphibians have been documented recently, particularly in the western United States (Corn and Fogleman 1984, Hayes and Jennings 1986, Bradford 1989, Corn et al. 1989, Carey 1993, Fellers and Drost 1993, Kagarise Sherman and Morton 1993, Blaustein 1994, Blaustein et al. 1994*b*). Many of these declines are due to obvious human alteration of breeding habitats (Hayes and Jennings 1986, Bradford 1989, Corn 1994, Pechmann and Wilbur 1994) and other declines are likely attributable to natural and random processes (Corn and Fogleman 1984, Pechmann et al. 1991, Pechmann and Wilbur 1994). However, when a common species declines synchronously over a wide area without apparent habitat degradation, for example boreal toads (*Bufo boreas*) since about 1975 in the southern Rocky Mountains (Corn et al. 1989, Carey 1993, Stuart and Painter 1994), random events are an unlikely explanation and other anthropogenic causes must be investigated.

Acidification of amphibian habitats has been investigated as one possible cause of widespread amphibian declines. Natterjack toads (*B. calamita*) in Britain may have declined due to long-term, persistent (chronic) acidification of breeding habitats (Beebee et al. 1990), but no examples of amphibian declines in North America have been attributed to acidification despite numerous studies of the effects of acid conditions on amphibian embryos (see reviews by Freda et al. 1991, Pierce 1985). Corn and Vertucci (1992) and Bradford et al. (1992, 1994) concluded that there was no evidence for chronic acidification of amphibian habitats in the mountains of western North America.

Short-term decreases in the acid-neutralizing capacity (ANC) of surface waters during hydrological events like precipitation or snowmelt have been referred to as episodic acidification (Wigington et al. 1990, 1992), which can result in a short-term loss of all acid-neutralizing capacity (ANC <0 $\mu mol_c/L$), at which time effects on aquatic biota may occur due to increased concentrations of hydrogen ions and metals like aluminum (Baker et al. 1990). Despite the large volume of research on acidic deposition, episodic acidification events and the effects of acidification on species other than fish are under-represented in the literature (Schindler 1992). However, Harte and Hoffman (1989) hypothesized that episodic acidification had caused a de-

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cline of tiger salamanders (*Ambystoma tigrinum*) in Colorado.

Contrary to the situation in eastern North America, where spring and summer rainstorms are the dominant hydrologic events that influence the chemistry of amphibian breeding habitats (Freda et al. 1991), episodic acidification events in high-elevation amphibian habitats in the West occur largely during snowmelt. We have suggested that life history traits of most amphibian species made them unlikely to be exposed to potential episodes of acidification during snowmelt (Corn and Vertucci 1992). A full assessment of episodic acidification as a cause of amphibian declines requires careful documentation of water chemistry changes associated with the timing of actual breeding or presence of sensitive amphibian life stages.

Identifying episodic acidification

Episodic acidification events may be ''natural'' or associated with the effects of atmospheric deposition of strong acids. Defining or quantifying acidification as pH decline is not advocated due to both the difficulties in measuring pH (Metcalf 1984, Turk 1988, Asbury et al. 1989) and the nonconservative behavior of pH with respect to CO_2 (Stumm and Morgan 1981). The possible mechanisms responsible for episodic acidification can be illustrated using a charge-balance definition of ANC, which is applicable to most surface waters. If organic-acid and aluminum concentrations are low, then ANC is equivalent to carbonate–bicarbonate alkalinity, which can be defined by Alkalinity $= C_b - C_a$, where C_b is the sum of the concentrations of charges on the base cations Ca^{2+}, Mg^{2+}, Na^+, K^+, and NH_4^+, and C_a is the sum of the concentrations of charges on the acid anions NO_3^-, SO_4^{2-}, F^-, and Cl^-. Unanalyzed heavy-metal cations could influence this charge-balance definition of alkalinity, and anthropogenic deposition of trace metals does occur in pristine ecosystems (Nriagu and Pacyna 1988). However, concentrations of trace metals are too low to materially affect charge balance, so these are routinely disregarded in calculating alkalinity (e.g., Wigington et al. 1990, Vertucci and Eilers 1993).

Natural declines in ANC may occur during snowmelt as dilute melt waters increase their contribution to stream flow and pre-episode surface-water cation concentrations are diluted. Episodes of acidification are produced by the dilution of base cations if the decrease in C_b is greater than any decrease in C_a. Dilution cannot by itself cause acidic episodes where ANC <0 $\mu mol_c/L$. Other natural episodic acidification events can be caused by: a ''salt effect'' in coastal areas where cations deposited in saline precipitation exchange with adsorbed protons in the soil, reducing surface-water ANC during periods of high flow (Wright et al. 1988, Heath et al. 1992); increased CO_2 due to microbial respiration, where increased pCO_2 decreases pH but leaves alkalinity unchanged (Kratz et al. 1987); soil nitrification, which can generate acidity and NO_3^- thereby increasing C_a relative to C_b (Galloway et al. 1987); and organic-acid pulses from soil layers, where ANC decline is not associated with either C_b decrease or an increase in C_a (Denning et al. 1991).

The amount of episodic acidification potentially due to acidic deposition is the amount of ANC decline in excess of the decline in base-cation concentrations (dilution) or increase in organic acids. To quantify the actual amount of episodic acidification due to acidic deposition, the acid anions (i.e., NO_3^- and SO_4^{2-}) associated with the ANC decline must be from the atmospheric deposition of nitric and sulfuric acids and not other natural sources. Sea salt effects are evidenced by a depression of the Na^+ to Cl^- ratios in surface waters and are likely only in coastal areas. Organic-acid episodes can be distinguished by highly colored event waters with high dissolved organic carbon (DOC) concentrations or large apparent anion deficits. Increased pCO_2 due to microbial activity will only reduce pH and not affect ANC. Increased C_a resulting from nitrification is difficult to distinguish from deposition sources of nitrate but will be characterized by very high levels of surface-water nitrate concentrations relative to sulfate.

In this paper, we examine three sets of data for evidence of episodic acidification of amphibian breeding habitats in the Rocky Mountains, describe the phenology of amphibian breeding relative to potential episodic acidification, and describe how to document episodic anthropogenic acidification.

METHODS

Data sources and study sites

We examined published data from two locations for evidence of anthropogenic episodic acidification: the West Glacier Lake outlet, Albany County, Wyoming, in the Medicine Bow Mountains (Vertucci 1988, Reuss et al. 1993); and the ponds in the Mexican Cut Nature Preserve, Gunnison County, Colorado, in the Elk Mountains (Blanchard et al. 1987, Harte and Hoffman 1989, Wissinger and Whiteman 1992). West Glacier Lake is permanent, and the Mexican Cut ponds are a mixture of small temporary and semi-permanent ponds. In addition to these published studies, from 1987 through 1990 we monitored amphibian breeding activity and water chemistry at three sites in Larimer County, Colorado, between the Never Summer Mountains and the Medicine Bow Mountains: Matthews Pond (2800 m elevation, 40°35′44″ N, 105°50′42″ W), Lily Pond (2900 m, 40°34′27″ N, 105°50′36″ W), and Trap Lake (3050 m, 40°33′36″ N, 105°48′36″ W). Lily and Matthews ponds are snowmelt-filled vernal ponds that are dry in most years by late summer, and Trap Lake is a permanent drainage lake.

During our observations, two of the Larimer County sites had breeding amphibians. Chorus frogs (*Pseu-*

dacris triseriata) bred at Matthews Pond and Lily Pond and wood frogs (*Rana sylvatica*) bred at Matthews Pond. Two sites have lost amphibian populations: *B. boreas* and *P. triseriata* at Trap Lake, and *B. boreas* and *R. sylvatica* at Lily Pond (Corn et al. 1989). Also, *P. triseriata* has undergone a long-term decline at Lily Pond. From 1961 to 1973, numbers of breeding males fluctuated annually from ≈500 to 1500 individuals, but since 1986, the annual estimate of breeding males has varied between 45 and 140 animals (Corn et al. 1989; P. S. Corn, *unpublished data*).

Water chemistry

We collected water samples weekly during snowmelt and the amphibian breeding seasons at Lily Pond and Matthews Pond during 1987–1990 and Trap Lake during 1988–1990. Each sample was taken in a 250-mL, opaque, high-density polyethylene bottle from the breeding habitat in the littoral zone. Unfiltered samples were kept refrigerated before they were delivered for analysis. Water samples collected in 1987 were analyzed by the Soils Testing Laboratory at Colorado State University. All subsequent samples were analyzed by the Water Analysis Laboratory at the U.S. Forest Service Rocky Mountain Forest and Range Experiment Station in Fort Collins (Corn and Vertucci 1992). At both laboratories, pH was measured electrometrically with a glass electrode, and ANC was determined by Gran titration (Gran 1952). Major anions and cations were measured following methods recommended for studies of acid deposition (U.S. Environmental Protection Agency 1987).

Data on water chemistry from the Mexican Cut ponds used by Harte and Hoffman (1989) were taken as described in Blanchard et al. (1987). Data on water chemistry from the Mexican Cut ponds (obtained from Wissinger and Whiteman 1992), and West Glacier Lake outlet (obtained from Vertucci 1988 and Reuss et al. 1993), were also analyzed by the Forest Service laboratory in Fort Collins.

Results and Discussion

Episodic acidification of West Glacier Lake outlet

Monitoring of water chemistry at West Glacier Lake outlet began with the first meltwater-generated flow on 24 May (Fig. 1). Liquid water present in the outlet flume before this date was derived directly from melting of the snowpack above the flume. Such meltwater is acidic but is not representative of the lake outlet or any potential amphibian habitat. While snowmelt, as sampled from lysimeters adjacent to the lake, is acidic, $C_a > C_b$ and ANC = −20 $\mu mol_c/L$ (Vertucci and Conrad 1994), the lake outlet water derived from a mixture of snowmelt and water after contact with the watershed soils and rock is not acidic (ANC >0 $\mu mol_c/L$; Fig. 1).

Daily sampling of outlet chemistry during early snowmelt indicated a subtle episodic acidification event (Vertucci 1988). During the winter and fall, base-cation concentrations and ANC at the lake outlet were relatively high, about 100 and 65 $\mu mol_c/L$, respectively. As initial snowmelt-generated outlet flow from day 144 of the year (24 May) through day 150 (30 May), the concentration of base cations initially decreased <10 $\mu mol_c/L$. The ANC dropped ≈30 $\mu mol_c/L$ and the acid anions increased 20 $\mu mol_c/L$, resulting in an apparent anthropogenic episodic acidification of ≈20 $\mu mol_c/L$. The continuing decline in ANC after 30 May coincided with declines in both acid anions and base cations. Thus, the continued decline in ANC was due to the increasing dominance of dilute snowmelt waters, not anthropogenic acidification. Only with near-daily sampling during the initial snowmelt period were we able to detect any evidence of episodic acidification consistent with an anthropogenic source of the strong acids present in deposition and delivered to the lake via snowmelt (Vertucci 1988). Although the snowpack was slightly acidic each year, no acidic episodes (ANC <0 $\mu mol_c/L$) were recorded at the lake outlet during the subsequent 3 yr of monitoring (Reuss et al. 1993).

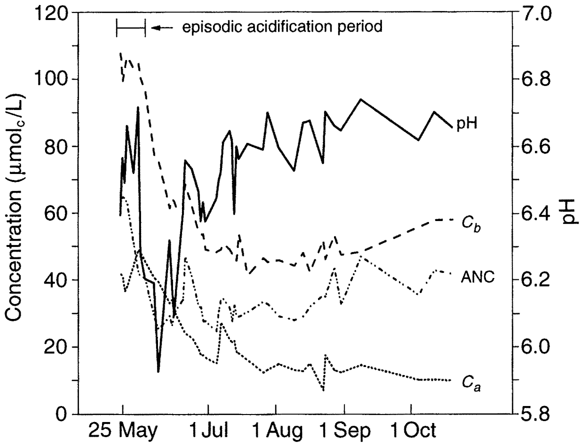

FIG. 1. Episodic acidification in 1988 at West Glacier Lake Outlet, Wyoming.

Episodic acidification in the central Rocky Mountains of Colorado

Complete major cation and anion data are available from Pond L-12 at Mexican Cut during spring and summer of 1984 and 1985 (Blanchard et al. 1987) and 1991 (Wissinger and Whiteman 1992). Except for the first samples in 1984 and 1985, there is no evidence of acidic conditions in this habitat or of any episodic acidification associated with strong acid anions (Blanchard et al. 1987; Fig. 2). The pattern of ANC, C_b, and C_a was similar each year and clearly shows that the seasonal pattern of ANC is directly related to changes in C_b (dilution) and is relatively unaffected by C_a. According to Blanchard et al. (1987), the early acidic samples in 1984 and 1985 were collected from above

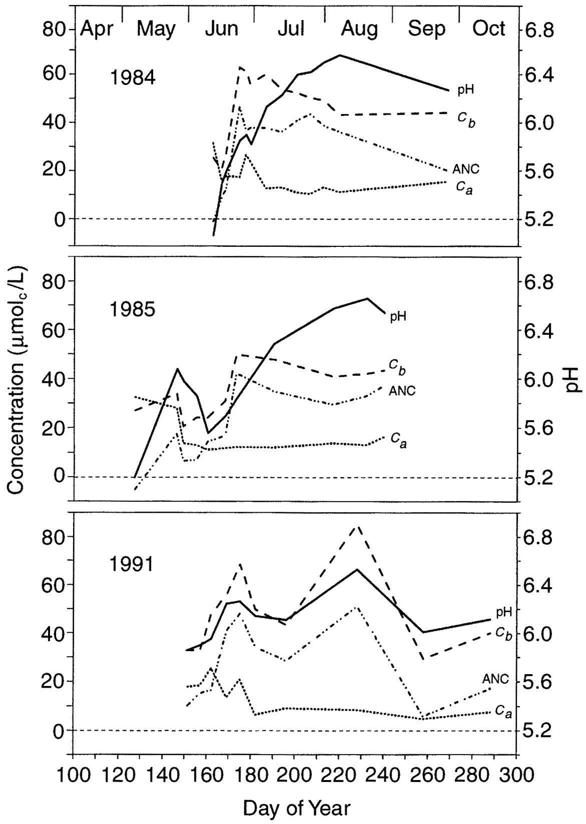

FIG. 2. Episodic acidification at Pond L–12 at Mexican Cut, Colorado. The data are from Blanchard et al. (1987) and Wissinger and Whiteman (1992).

the frozen pond surface. Such samples clearly represent the chemistry of local snowmelt, not the breeding habitat of *A. tigrinum.* For example, samples collected above the frozen pond surface on 7 May 1985 had pH = 5, C_b = 27 μmol$_c$/L, C_a = 33 μmol$_c$/L, and ANC (calculated from $C_b - C_a$) = −6 μmol$_c$/L. Samples collected from beneath the ice on 7 May 1985, where *A. tigrinum* could have been breeding, showed pH = 5.92, ANC = 33 μmol$_c$/L, C_b = 75 μmol$_c$/L, and C_a = 53 μmol$_c$/L, and these samples neither were acidic nor evidenced anthropogenic episodic acidification (Blanchard et al. 1987).

Episodic acidification of Front Range amphibian habitats

Intervals of ≈100 m of elevation separated the three ponds we surveyed. Consequently, in most years snowmelt lagged by ≈1 wk at each step from Matthews Pond to Lily Pond to Trap Lake. We did not sample Matthews Pond early enough to see initial snowmelt in any year (Table 1). However, at Lily Pond (Table 2) and Trap Lake (Table 3) our initial water samples were taken before the appearance of surface water and breeding amphibians. There is no evidence of either anthropogenic episodic acidification or acidic conditions at any site in any year (Tables 1–3). Minimum ANC values are associated with low base-cation concentrations (C_b), not elevated concentrations of acid anions (C_a). All three of these sites showed discrepancies between ANC and ($C_b - C_a$) attributable to organic acids. Dissolved organic carbon (DOC) was measured occasionally and was highest at Matthews Pond (>20 mg/L), intermediate at Lily Pond (8–15 mg/L), and lowest at Trap Lake (5–8 mg/L). There is no evidence that organic acids produced acidification episodes at these sites. The discrepancy observed between ANC and ($C_b - C_a$) was greatest at Matthews Pond, the high-DOC habitat, consistent with an anion charge of 4 μmol$_c$/L per milligram of DOC.

As with snowmelt, we did not observe Matthews Pond before frogs began breeding except in 1988, when breeding by *R. sylvatica* and *P. triseriata* began after 8 May (Table 1). Both frogs, however, had prolonged breeding seasons with most eggs laid after all of the surface ice and much of the snow in the surrounding forest had melted. *Rana sylvatica* is well known as an explosive breeder elsewhere in its range (Seale 1982), but in all 4 yr at Matthews Pond, eggs were deposited fairly uniformly over periods of ≈2 wk. We have less information about actual deposition of eggs by female *P. triseriata*, which distribute their clutches in several small egg masses that are difficult to detect. At one site at a lower elevation in Colorado, however, breeding activity by male *P. triseriata* occurred over 6 wk, and gravid females were present throughout (Corn 1980).

At Lily Pond, no *P. triseriata* were observed until ice covered ≤50% of the pond's surface (Table 2). Trap Lake historically had a large population of *B. boreas* (Corn et al. 1989), but we observed toads at this site only in 1987. That year, we found a few males and one spoiled egg mass on 11 June. We did not collect serial water samples at Trap Lake in 1987, but snowmelt that year was the earliest of the period 1987–1990. *Bufo boreas* breeds latest in the year of all the amphibians in the mountains of Colorado (Corn and Vertucci 1992).

Our analysis of water chemistry during snowmelt at Matthews Pond, Lily Pond, and Trap Lake failed to reveal evidence of anthropogenic episodic acidification. But, as we concluded from the West Glacier Lake data, daily samples during the earliest snowmelt may be necessary to detect an episode of anthropogenic acidification, and our samples at these three sites were not frequent or early enough to satisfy that requirement. However, all three species of anurans bred after open water appeared on the ponds, long past initial snowmelt and any potential acidification episode. Regardless of the timing of breeding, mortality of amphibian embryos that resulted from exposure to low pH was unlikely. In laboratory exposures of embryos to acid conditions, the pHs lethal to 50% of *B. boreas*, *P. triseriata*, and *R. sylvatica* individuals obtained from our research sites were 4.5, 4.8, and 4.3, and the lowest pHs with no significant mortality were 4.9, 5.2, and 4.6, respec-

TABLE 1. Breeding activity of *Pseudacris triseriata* (PSTR) and *Rana sylvatica* (RASY), ice and snow conditions, and water chemistry at Matthews Pond, Larimer County, Colorado, in 1987–1990.

Date	Amphibian breeding activity	Ice condition	Snowpack surrounding pond	pH	Acid-neutralizing capacity (μmol$_c$/L HCO_3)	Acid anions, C_a (μmol$_c$/L)	Base cations, C_b (μmol$_c$/L)
1987 season:							
29 April	PSTR calling; 2 RASY egg masses	<10% ice cover	complete	7.0	119	49	112
6 May	PSTR calling; 25 new RASY egg masses	open water	patchy	7.2	159	49	252
14 May	PSTR calling; 11 new RASY egg masses		patchy	6.9	150	32	265
21 May	PSTR, RASY calling		gone	7.0	146	37	247
27 May	PSTR, RASY calling			7.1	166	35	250
1988 season:							
8 May	none	90% ice	complete	6.0	159	33	210
15 May	PSTR calling; 2 RASY egg masses	open water	complete	6.1	112	43	207
23 May	PSTR calling; 7 new RASY egg masses		patchy	6.1	108	54	247
30 May	PSTR calling; 9 new RASY egg masses		patchy	6.0	133	48	279
5 June	PSTR, RASY calling		gone	···	···	···	···
12 June	none			6.1	176	46	345
1989 season:							
3 May	1 RASY egg mass	30% ice	complete	6.2	144	52	289
11 May	PSTR calling; 12 new RASY egg masses	open water	patchy	6.3	133	63	271
18 May	PSTR calling; 9 new RASY egg masses		patchy	6.2	164	76	274
25 May	PSTR calling; 1 new RASY egg mass		gone	6.6	149	80	330
1 June	none			6.2	186	78	357
1990 season:							
23 May	PSTR calling; 8 RASY egg masses	open water	complete	6.2	123	62	215
30 May	PSTR, RASY calling		patchy	6.5	135	60	236
6 June	PSTR calling; 7 new RASY egg masses		patchy	6.3	161	66	320
13 June	PSTR, RASY calling		gone	6.1	169	57	315

tively (Corn et al. 1989, Corn and Vertucci 1992). The lowest pH we recorded at Matthews Pond, Lily Pond, or Trap Lake was 5.8 on 11 May 1989 at Lily Pond (Table 2), apparently before *P. triseriata* had begun to breed. All other pHs recorded at these three ponds were ≥6.0. The pH of the outflow from West Glacier Lake was <6.0 during two short early snowmelt episodes in 1988 and 1989 (Reuss et al. 1993).

It is uncertain whether *A. tigrinum* embryos are exposed to acidic conditions. Harte and Hoffman (1989) inferred that *A. tigrinum* embryos were in association with acidic pond waters at Mexican Cut Pond L–12, but no direct observations were made of salamander breeding activity. Wissinger and Whiteman (1992), however, documented *A. tigrinum* breeding activity at Mexican Cut from 1989 to 1991, and found that embryos were absent during early snowmelt (embryos were not present until mid to late June, long after initial snowmelt) and chemical conditions were never acidic.

Analysis of snowmelt water chemistry from southern Wyoming and northern and central Colorado does not indicate a regional threat of episodic acidification for amphibians, but Corn and Vertucci (1992) suggested that a localized "hot spot" could exist in the Park Range in Colorado. Turk (1995) found that this area, north of Rabbit Ears Pass in Routt and Jackson counties, has the highest concentration in snow of SO_4^{2-}, NO_3^-, and H^+ in the Rocky Mountains. ANC of surface waters in this area is low, so potential exists now for biological damage from episodic acidification (Turk 1995). However, because Turk's measurements were taken at elevations above those occupied by amphibians, the magnitude of threat to amphibian breeding habitats is unknown.

Episodic acidification and documented amphibian declines

Recent declines of *B. boreas* in the southern Rocky Mountains resulted in a petition to the U.S. Fish and Wildlife Service to list these populations as endangered (U.S. Fish and Wildlife Service 1994). In 1994, *Bufo boreas* was listed as endangered in Colorado by the Colorado Division of Wildlife. This decline cannot be attributed to episodic acidification. The breeding phenology of this species does not coincide with potential episodes of acidification (Corn and Vertucci 1992; Fig. 3); therefore, direct mortality of embryos from exposure to low pH cannot occur.

Indirect effects may result from exposure to acidity at less than lethal concentrations. In amphibians these are usually manifested as reduced larval growth rates (Pierce and Wooten 1992), but alteration in food supplies and stress that might compromise immune system function are two other possible results. Reduced larval growth may have a variety of consequences, all of which reduce fitness. Pierce and Montgomery (1989)

TABLE 2. Breeding activity of *Pseudacris triseriata,* ice and snow conditions, and water chemistry at Lily Pond, Larimer County, Colorado, in 1987–1990.

Date	Amphibian breeding activity	Ice condition	Snowpack surrounding pond	pH	Acid-neutral-izing capacity (μmol$_c$/L HCO_3)	Acid anions, C_a (μmol$_c$/L)	Base cations, C_b (μmol$_c$/L)
1987 season:							
29 April	none	100% ice	complete	6.8	90	34	148
6 May	none	90% ice	complete	6.7	79	28	138
14 May	PSTR calling	< 50% ice	patchy	6.8	119	36	208
21 May	PSTR calling	open water	patchy	7.0	112	37	176
27 May	PSTR calling		patchy	7.0	132	34	186
1988 season:							
15 May	none	100% ice	complete	6.1	107	47	170
23 May	none	25% ice	complete	6.0	84	30	161
30 May	PSTR calling	open water	patchy	7.1	111	···	189
5 June	PSTR calling		patchy	6.3	122	32	197
12 June	PSTR calling		patchy	6.4	141	28	215
20 June	PSTR calling		gone	6.9	168	26	246
27 June	none			7.0	185	21	263
1989 season:							
3 May	none	100% ice	complete	6.3	126	62	227
11 May	none	30% ice	complete	5.8	65	33	163
18 May	PSTR calling	10% ice	patchy	6.4	114	28	165
25 May	PSTR calling	open water	patchy	6.8	117	30	197
1 June	PSTR calling		gone	6.6	148	32	214
8 June	PSTR calling			6.6	150	31	212
1990 season:							
23 May	none	100% ice	complete	6.2	130	41	172
30 May	PSTR calling	50% ice	complete	6.5	111	30	144
6 June	PSTR calling	open water	patchy	6.6	124	30	203
13 June	PSTR calling		patchy	6.3	143	20	205
20 June	PSTR calling		gone	6.6	180	29	240

TABLE 3. Ice and snow conditions and water chemistry at Trap Lake, Larimer County, Colorado, in 1988–1990.

Date	Ice condition	Snowpack surrounding pond	pH	Acid-neutralizing capacity (μmol$_c$/L HCO_3)	Acid anions, C_a (μmol$_c$/L)	Base cations, C_b (μmol$_c$/L)
1988 season:						
15 May	100% ice	complete	6.3	110	50	175
23 May	100% ice	complete	6.3	111	46	198
30 May	10% ice	patchy	6.3	91	37	166
5 June	open water	patchy	6.6	122	33	191
12 June		patchy	6.1	103	19	220
20 June		gone	7.4	203	32	263
27 June			7.2	229	31	283
1989 season:						
3 May	100% ice	complete	6.6	329	118	443
11 May	100% ice	complete	6.4	156	65	238
18 May	90% ice	complete	6.3	72	81	181
25 May	open water	patchy	7.0	134	63	216
1 June		patchy	7.0	176	57	235
8 June		gone	7.2	225	58	288
1990 season:						
30 May	100% ice	complete	6.6	129	63	···
6 June	open water	patchy	6.8	141	55	193
13 June		patchy	6.8	179	53	238

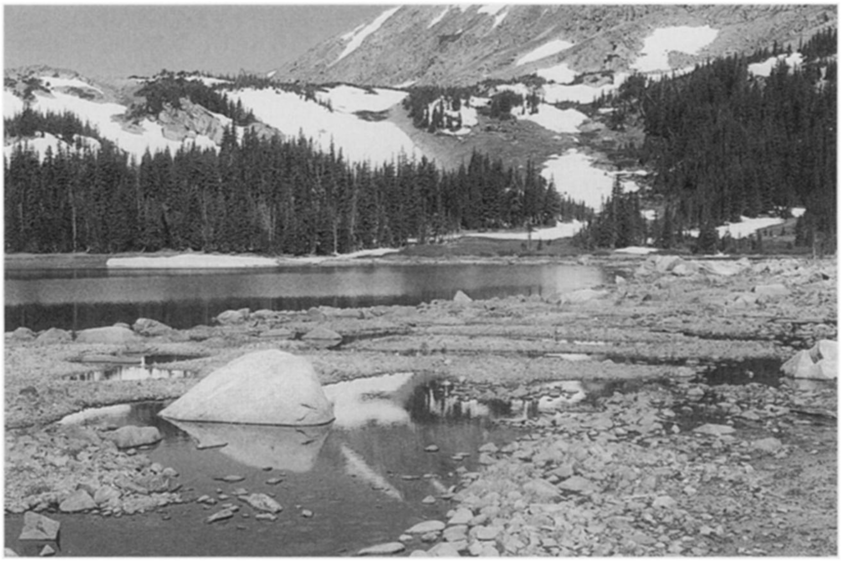

FIG. 3. North shoreline of Lost Lake, Rocky Mountain National Park, Colorado, on 6 June 1994, during the latter stages of snowmelt. Egg deposition by *Bufo boreas* occurred in the shallow pools in the foreground and at the margin of the lake from about 30 May to 8 June. Note the absence of snow on the north shore and the patchiness of the remaining snowpack.

exposed tadpoles of Woodhouse's toad (*B. woodhousei*) and the Gulf Coast toad (*B. valliceps*) to pH 4 for 3 d. Tadpoles stopped growing during this period, but after an additional 7 d at pH 7, wet mass did not differ significantly from that of tadpoles held at pH 7 for the entire 10 d. Reduced growth has seldom been observed outside the laboratory. In fact, Wissinger and Whiteman (1992) found that 2nd-yr larval *A. tigrinum* at Mexican Cut were larger in low-ANC ponds compared to high-ANC ponds. Carey (1993) observed adult *B. boreas* with symptoms of redleg disease, a bacterial infection. She hypothesized that a regional anthropogenic stress that suppressed immune system function was responsible for the declines of *B. boreas* in Colorado. This hypothesis has not been evaluated. Chronic acidification could alter the food supply of tadpoles, because it changes the species composition and reduces the diversity of phytoplankton (Findlay and Kasian 1986, Geelen and Leuven 1986, Stokes 1986, Charles et al. 1989). The effects on phytoplankton of a short pulse of acidity at the beginning of the growing season are not known, but phytoplankton assemblages in lakes in the western U.S. show no changes attributable to acidification (Baron et al. 1986, Charles et al. 1989, Toetz and Windell 1993). Indirect effects on embryonic, larval, or transformed *B. boreas* from episodic acidification are unlikely for the same reason that direct mortality of embryos is unlikely: potentially sensitive life stages of toads are not present when an acid pulse might occur. The decline of *B. boreas* in the southern Rocky Mountains is probably due to some factor other than acid deposition; for example, direct or indirect effects of increased ultraviolet radiation (Blaustein et al. 1994*a*), pesticides or contaminants from atmospheric transport, or heavy metals not measured in this study.

Leopard frogs (*Rana pipiens*) have declined in Colorado and Wyoming by a magnitude similar to that of *B. boreas* (Corn and Fogleman 1984, Corn et al. 1989, Corn 1994). This decline is also not likely to have been caused by episodic acidification, because *R. pipiens* generally occupy lakes that have high ANC and that are at lower elevations lacking extensive snowpack (Corn and Vertucci 1992).

CONCLUSIONS

Monitoring pH and ANC alone cannot provide evidence of anthropogenic episodic acidification of amphibian habitats. Besides pH and ANC, Freda et al. (1991) recommended measuring total Al, DOC, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, SO_4^{2-} and NO_3^{-}. To apply our criteria for detecting anthropogenic episodic acidification, other important acid anions should be measured (Cl^{-} and Fl^{-}). Also, the sampling frequency recommended by Freda et al. (1991), three samples during the breeding season, is insufficient to detect and characterize episodic acidification. Water samples must also be collected from the habitat where amphibians are present.

There is some evidence that anthropogenic episodic acidification may occur in high-elevation habitats in the Rocky Mountains, but there is no evidence that episodic acidification has led to acidic conditions (ANC <0) or that amphibian embryos are present during the initial phase of snowmelt when episodic acidification might occur. Our surveys of habitats where amphibians have declined in the Rocky Mountain region show no evidence of chronic episodic acidification as the cause of observed declines. Similarly, amphibian populations in sensitive habitats in the Sierra Nevada in California have not been found to be affected by current levels of acidic deposition (Bradford et al. 1992, 1994, Soiseth 1992). Declines of amphibians in the western United States may be due to many natural and anthropogenic factors, but acidic deposition does not appear to be one of them.

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