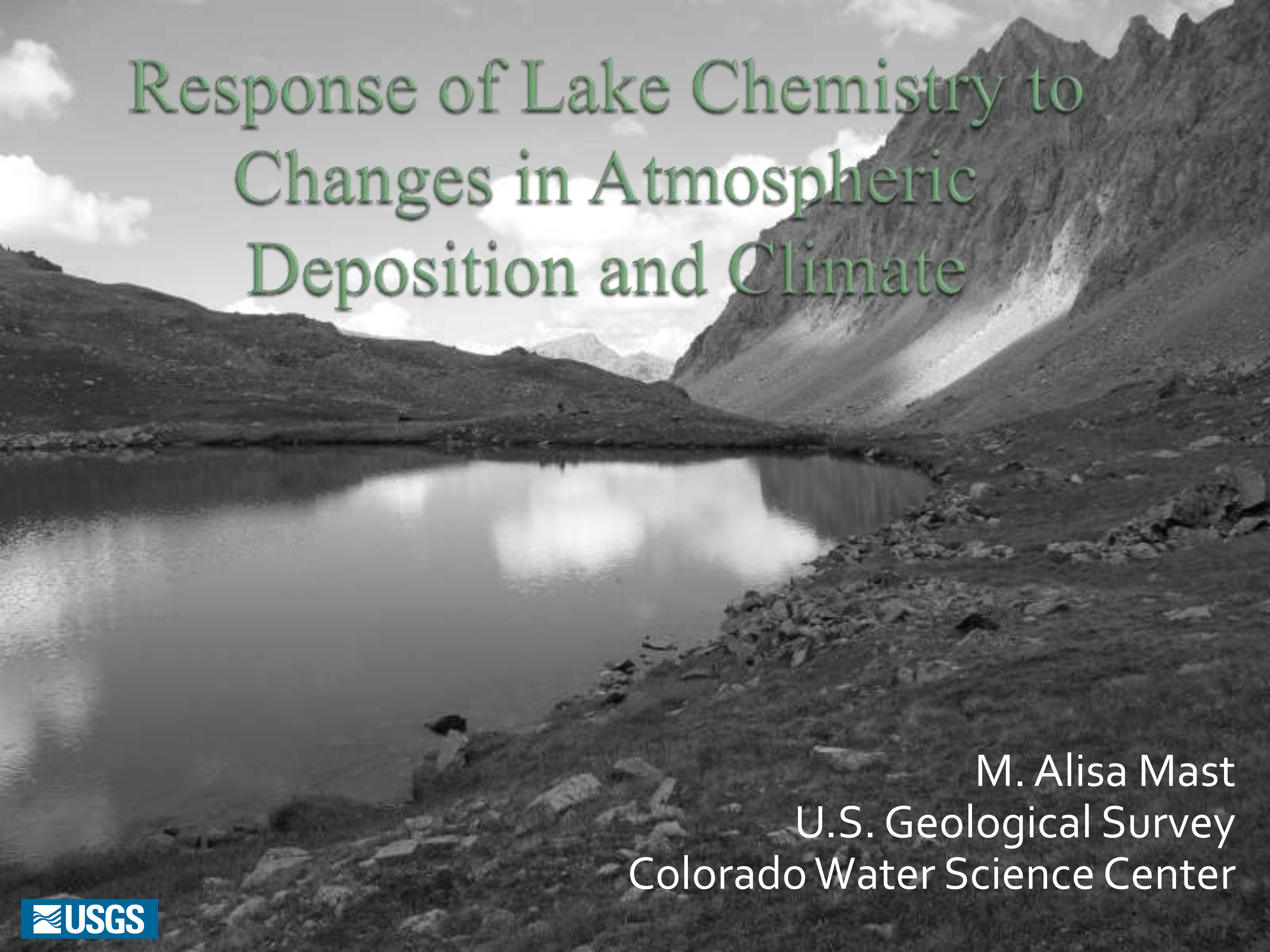

Response of Lake Chemistry to Changes in Atmospheric Deposition and Climate

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Colorado Water Science Center

USGS

Importance of Mountain Ecosystems

High-mountain environments sensitive to changes in atmospheric pollution and climate

May provide early-warning indicators for change in more resistant ecosystems of higher-order drainages

Generally have received less monitoring efforts than other landscapes types in the U.S.

Study Objective

Assess the effects of deposition and climate on lake chemistry in 3 Colorado wilderness areas

Approach :

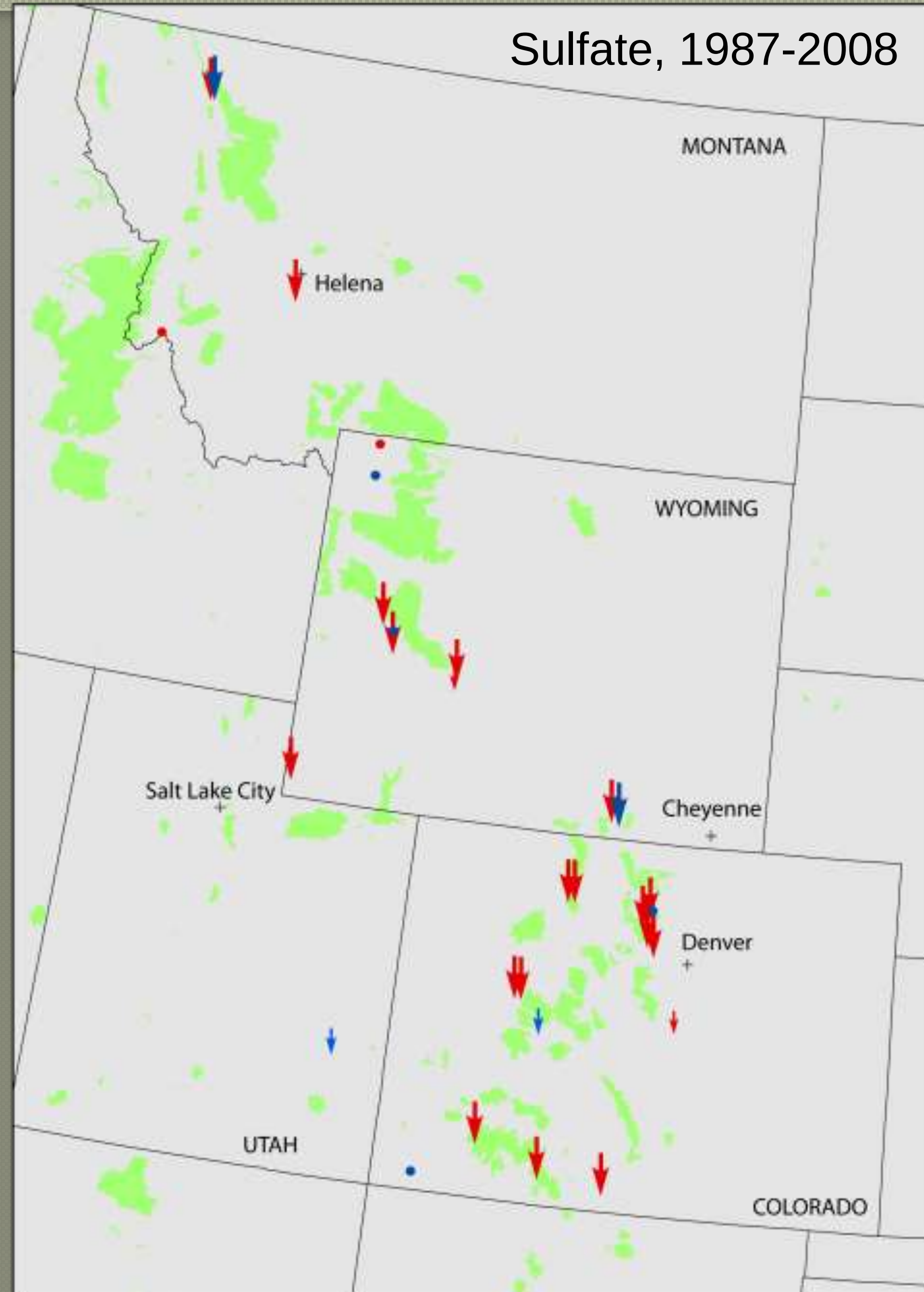
Trend analysis of long-term records including deposition, climate variables, and lake chemistry

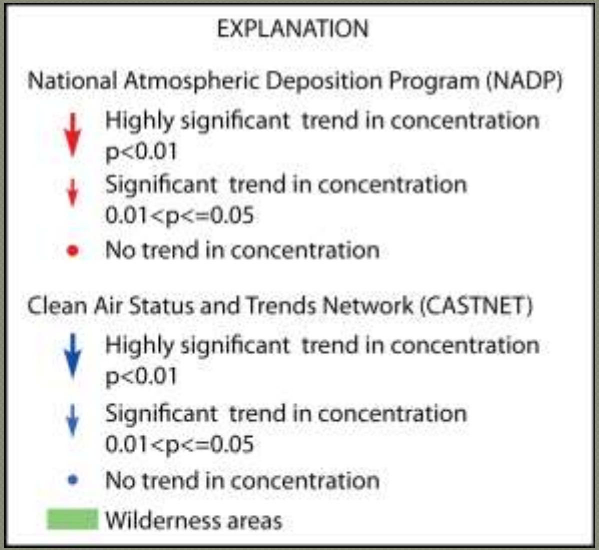
Deposition Data

- NADP (wet deposition) 1987
- CASTNET (dry deposition) 1989 or 1995
- USGS Snowpack Network

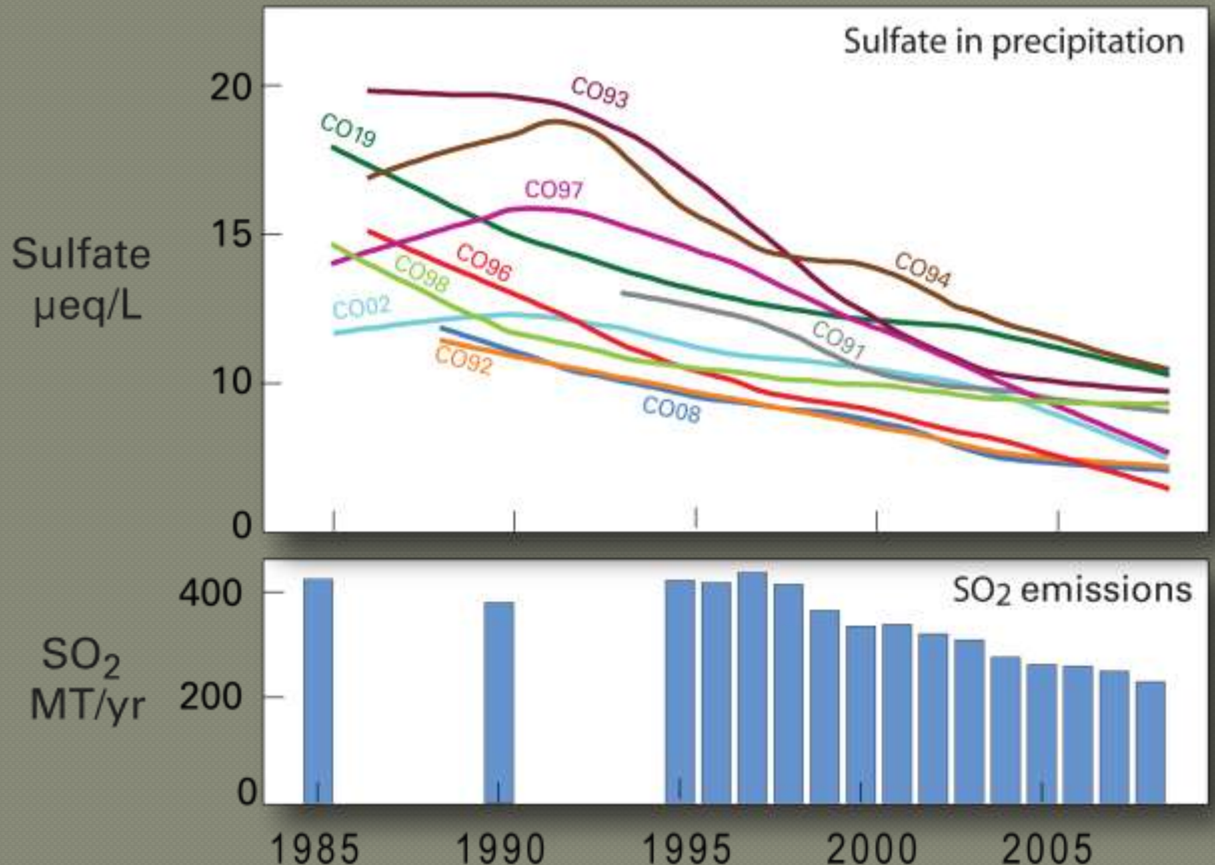
Summit Lake CO97

Sulfate in precipitation has decreased at most NADP stations in the Rocky Mountains over the past 2 decades





Declines in precipitation sulfate appear to reflect regional patterns in SO_2 emissions

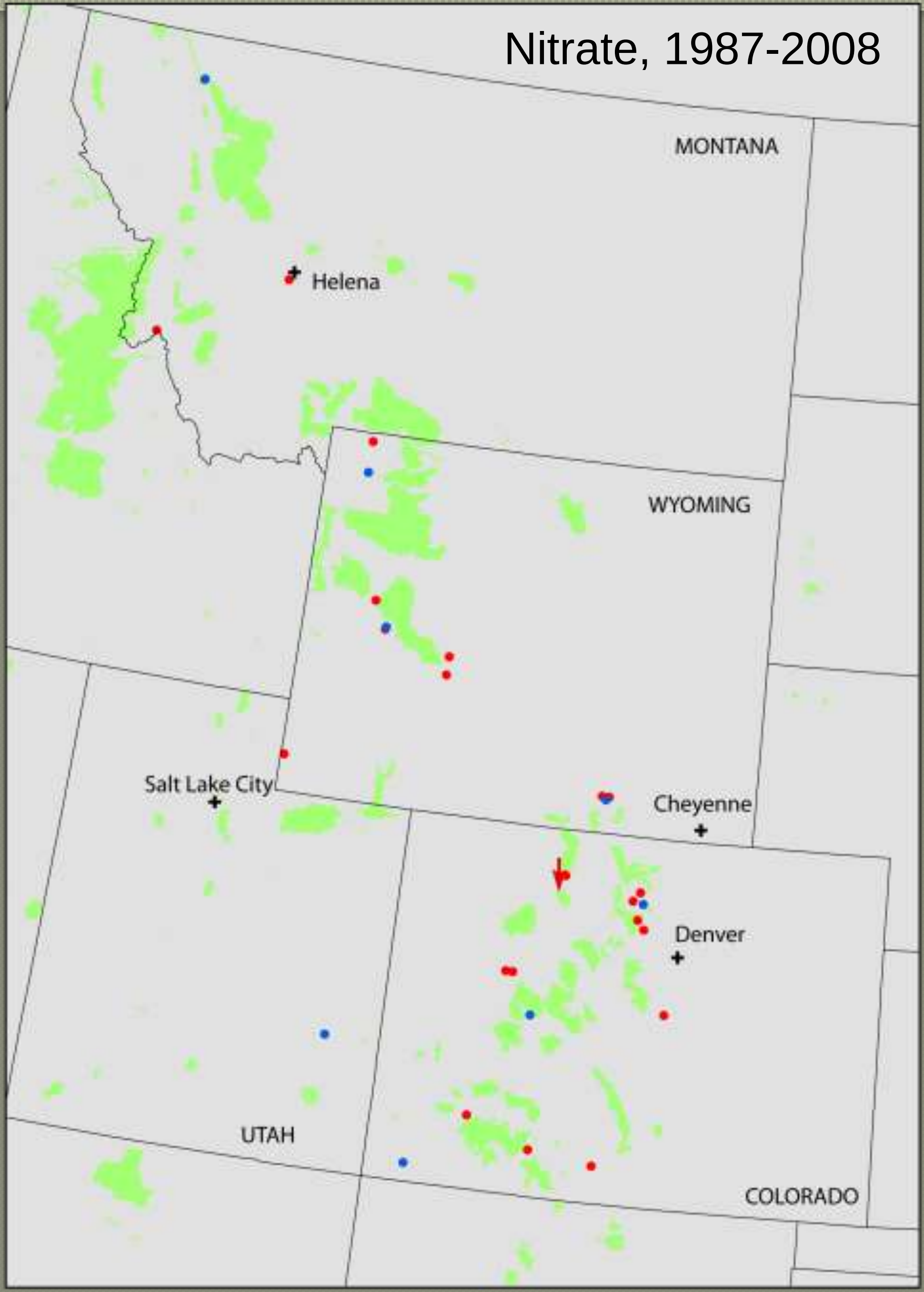


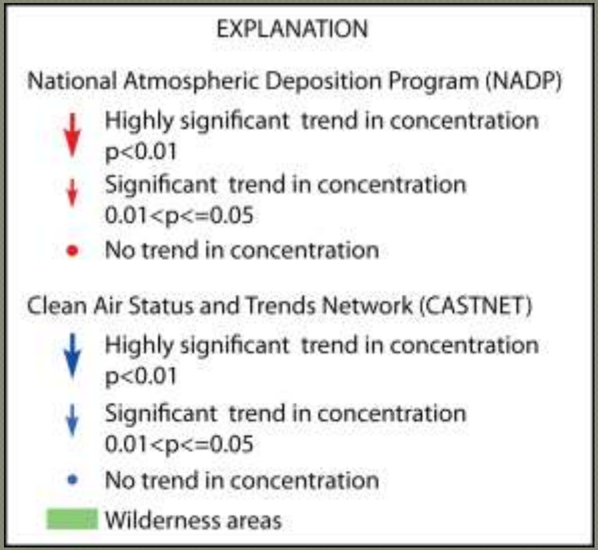
46% reduction

44% reduction

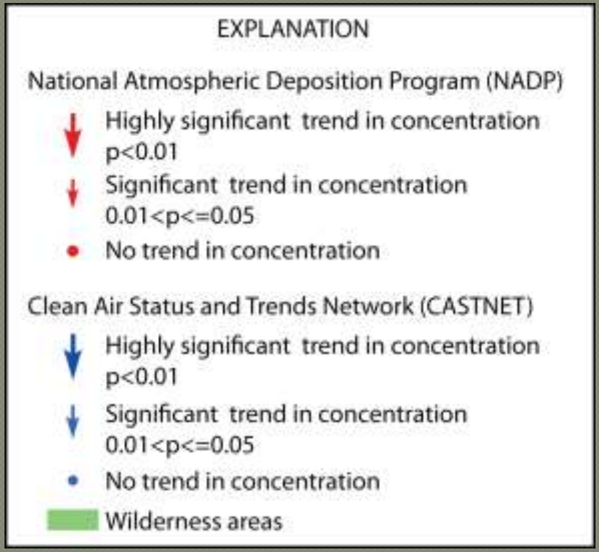
SO_2 emissions from http://camddataandmaps.epa.gov/gdm/

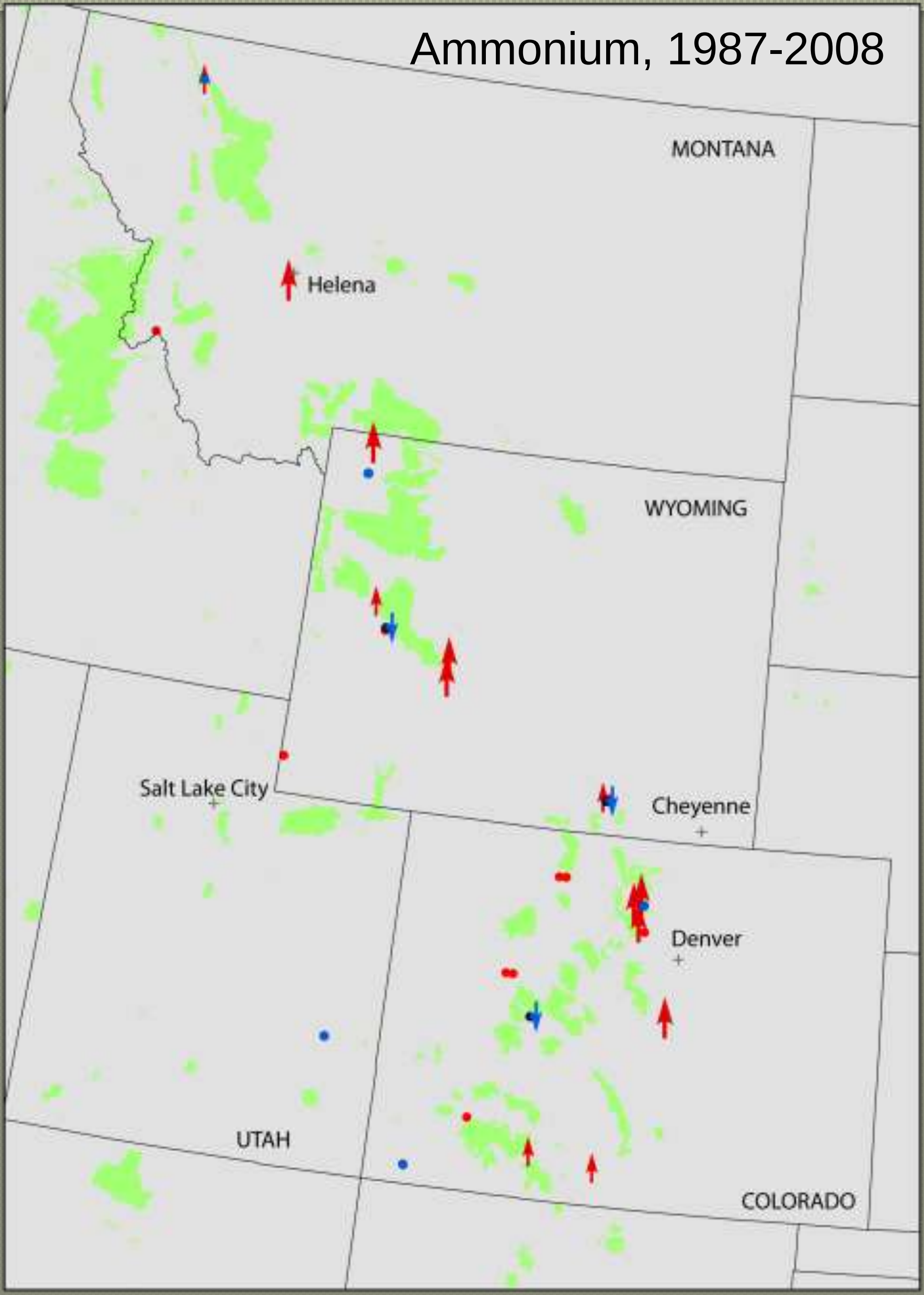
Trends in nitrogen species were not as widespread





Stations showing ammonium trends on east side of Continental Divide

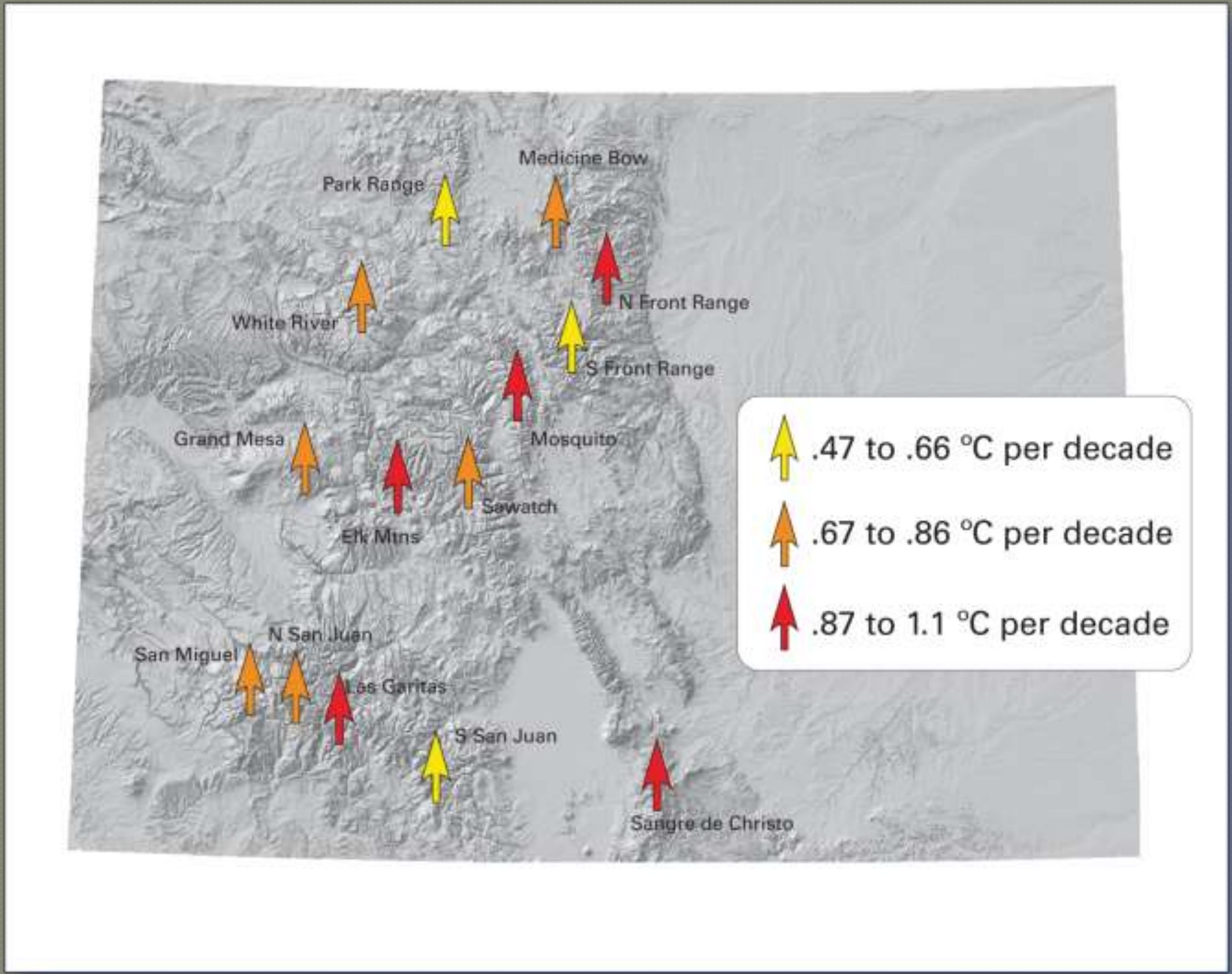




Climate Data

- Annual air temperature and precipitation amount at 77 SNOTEL stations (Clow, 2010)
  - Rigorous screening for outliers
  - Grouped by major mountain ranges
  - Trends analyzed using Regional Kendall Test
- Annual precipitation at NADP stations
- Snow-cover duration at SNOTEL stations

Trends in annual air temperature at Colorado SNOTEL stations, 1979-2008



By month, strongest trends in winter (Nov, Dec, Jan) and mid-summer (July)

Trends in Annual Precipitaton

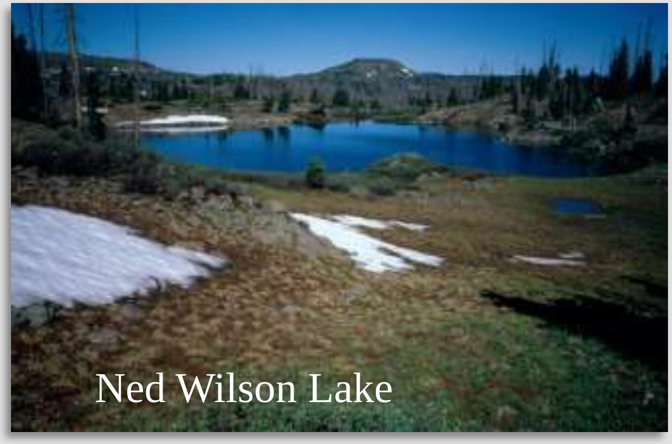
SNOTEL Groupings (1979-2007)

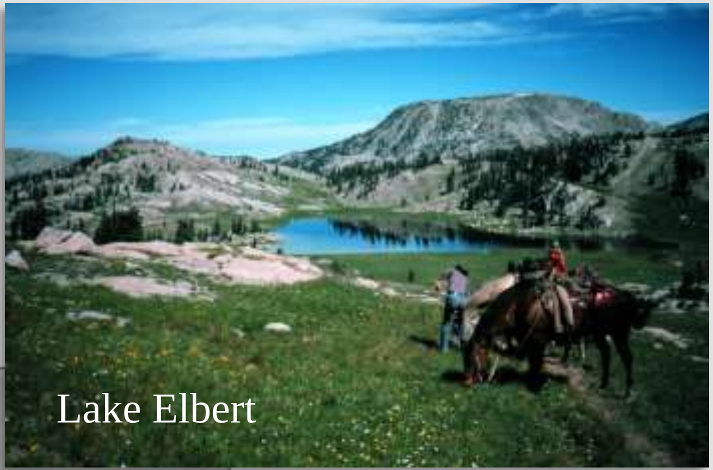
	cm/yr	p-value
Elk Mountains	-0.2	0.625
Grand Mesa	-0.2	0.590
Las Garitas	-0.4	0.095
Medicine Bow	-0.3	0.056
Mosquito	-0.1	0.624
Northern Front Range	-0.3	0.031
Northern San Juan	-0.3	0.101
Park Range	-0.2	0.300
San Miguel	-0.4	0.072
Sangre de Christo	-0.5	0.002
Sawatch	-0.4	0.000
Southern Front Range	-0.3	0.048
Southern San Juan	-0.5	0.100
White River Plateau	-0.3	0.188

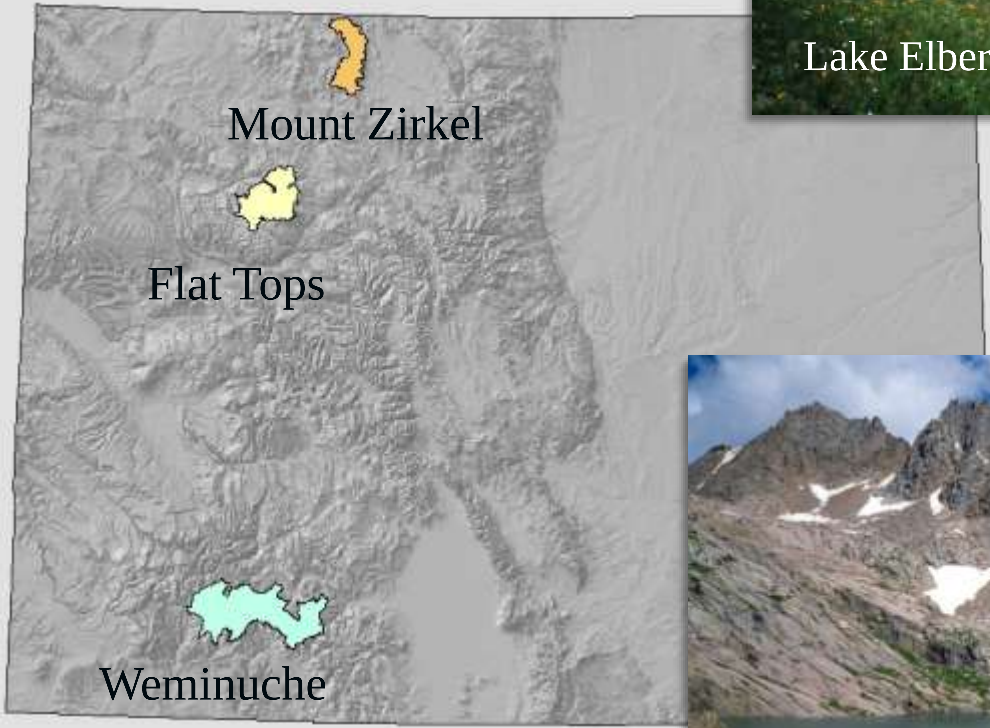
By season, decreases in winter precipitation were detected at 11 of 14 groupings suggesting a shift in the seasonal distribution of precipitation.

No significant trends in precipitation at NADP from 1987-2008

USGS Lakes Monitoring Program





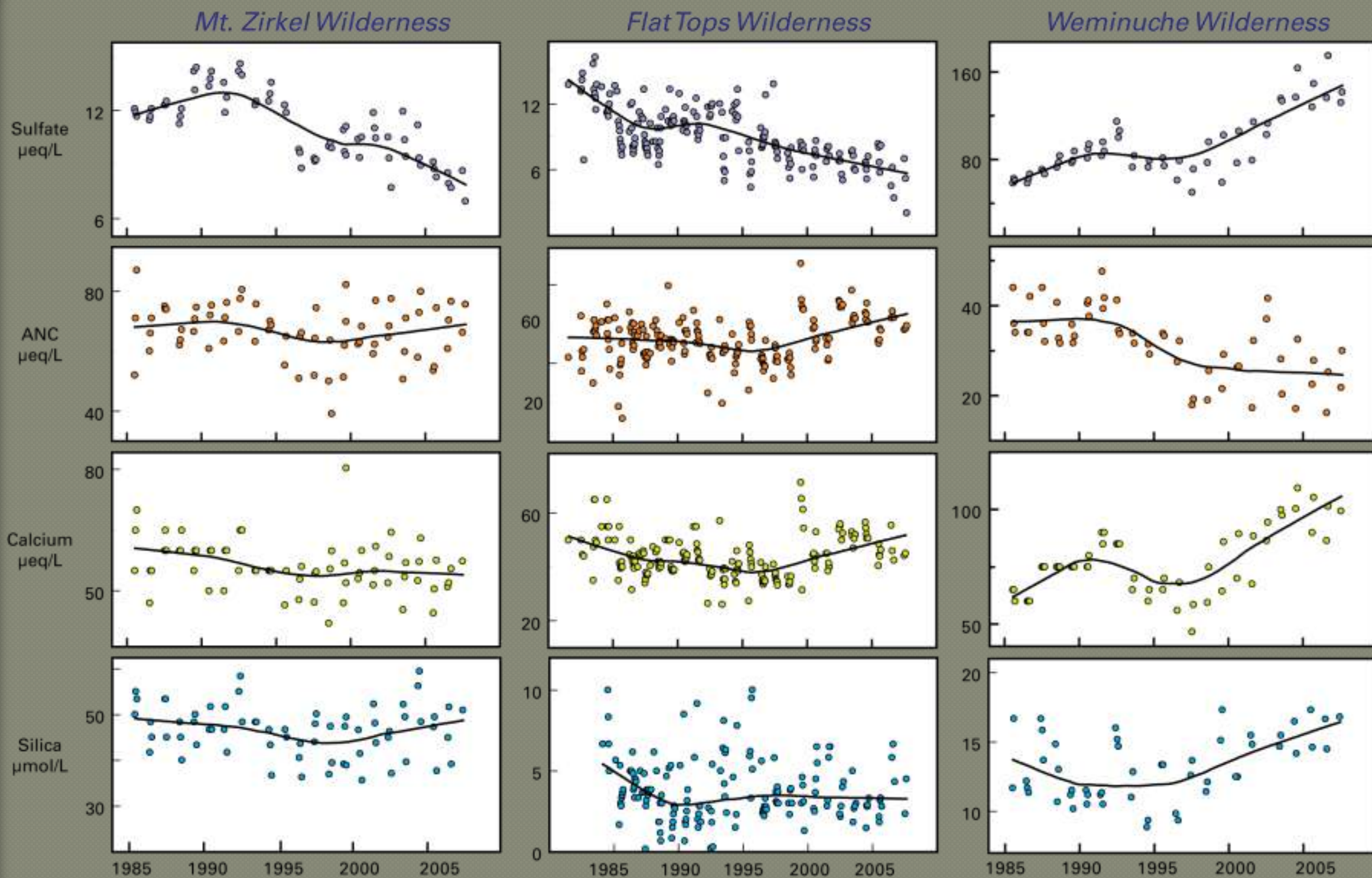


Current Monitoring Activities

- Mount Zirkel Wilderness Area (1983)
    - 3 Lakes (+inflows) sampled 3 times per year
    - 30 Lakes sampled once per year (last 2006)
- Weminuche Wilderness Area (1985)
    - 6 Lakes (+inflows) sampled 2-3 times per year
- Flat Tops Wilderness Area (1981)
    - 4 Lakes sampled
    - 3 times per year
- Major ions, nutrients, & DOC
- Funded by FS, CDPHE

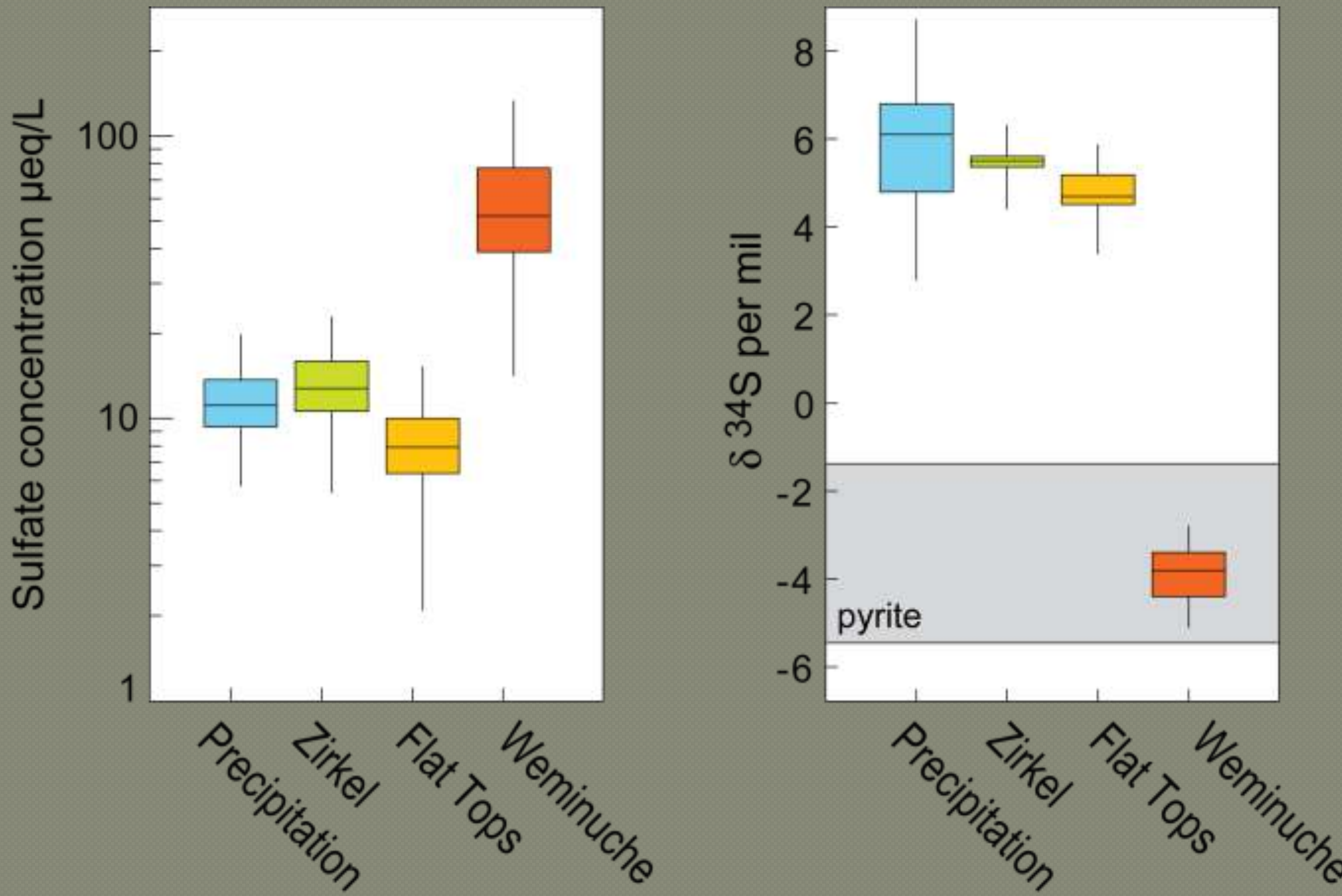

Grizzly Lake @ 13,100 ft

Trends in Lake Chemistry

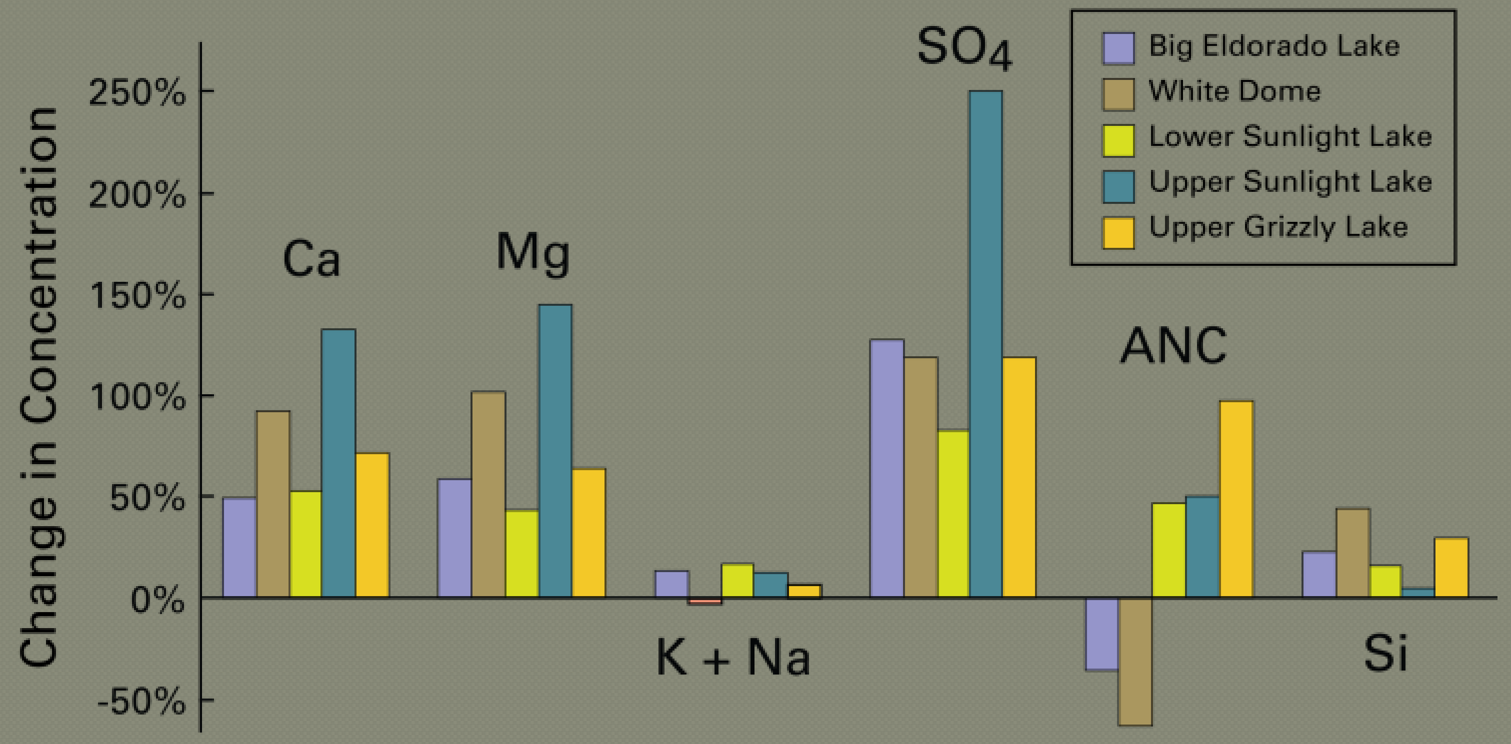


Station Name	ANC	Ca	Mg	Na	K	NO_3	Cl	SO_4	SiO_2
Flat Tops Wilderness									
Seven Lakes	↑	○	○	○	○		○	↓	↑
Lake Elbert	○	↓	○	○	○		○	↓	○
Summit Lake	↑	↑	↑	○	○		○	↓	↑
Mount Zirkel Wilderness									
Ned Wilson Lake	↑	↑	↑	○	○		○	↓	↑
Upper Ned Wilson Lake	↑	↑	↑	○	○		○	↓	↑
Lower Packtrail Pothole	↑	↑	↑	○	○		○	↓	↑
Upper Packtrail Pothole	↑	↑	↑	○	○		○	↓	○
Weminuche Wilderness									
Big Eldorado Lake	↓	↑	↑	○	○		○	↑	↑
Little Eldorado Lake	↓	↑	↑	○	○	○	○	↑	↑
White Dome Lake	○	↑	↑	○	○	↑	○	↑	↑
Lower Sunlight Lake	↑	↑	↑	○	○		○	↑	↑
Upper Sunlight Lake	↑	↑	↑	↑	↑	○	○	↑	↑
Upper Grizzly Lake	↑	↑	↑	○	○	○	○	↑	↑

Sources of Dissolved Sulfate



Changes in Chemical Composition of 5 Weminuche Lakes



Pyrite Oxidation

Pyrite + O_2 + H_2O ---> Iron Hydroxide + $2H^+$ + SO_4^{-2}

Strong Acid Weathering of Carbonate

$2H^+$ + SO_4^{-2} + Calcite ---> Ca^{+2} + SO_4^{-2}

Strong Acid Weathering of Chlorite

$2H^+$ + SO_4^{-2} + Chlorite ---> Mg^{+2} + SO_4^{-2} + Si + Clay

Ion Exchange with Clays & Minerals

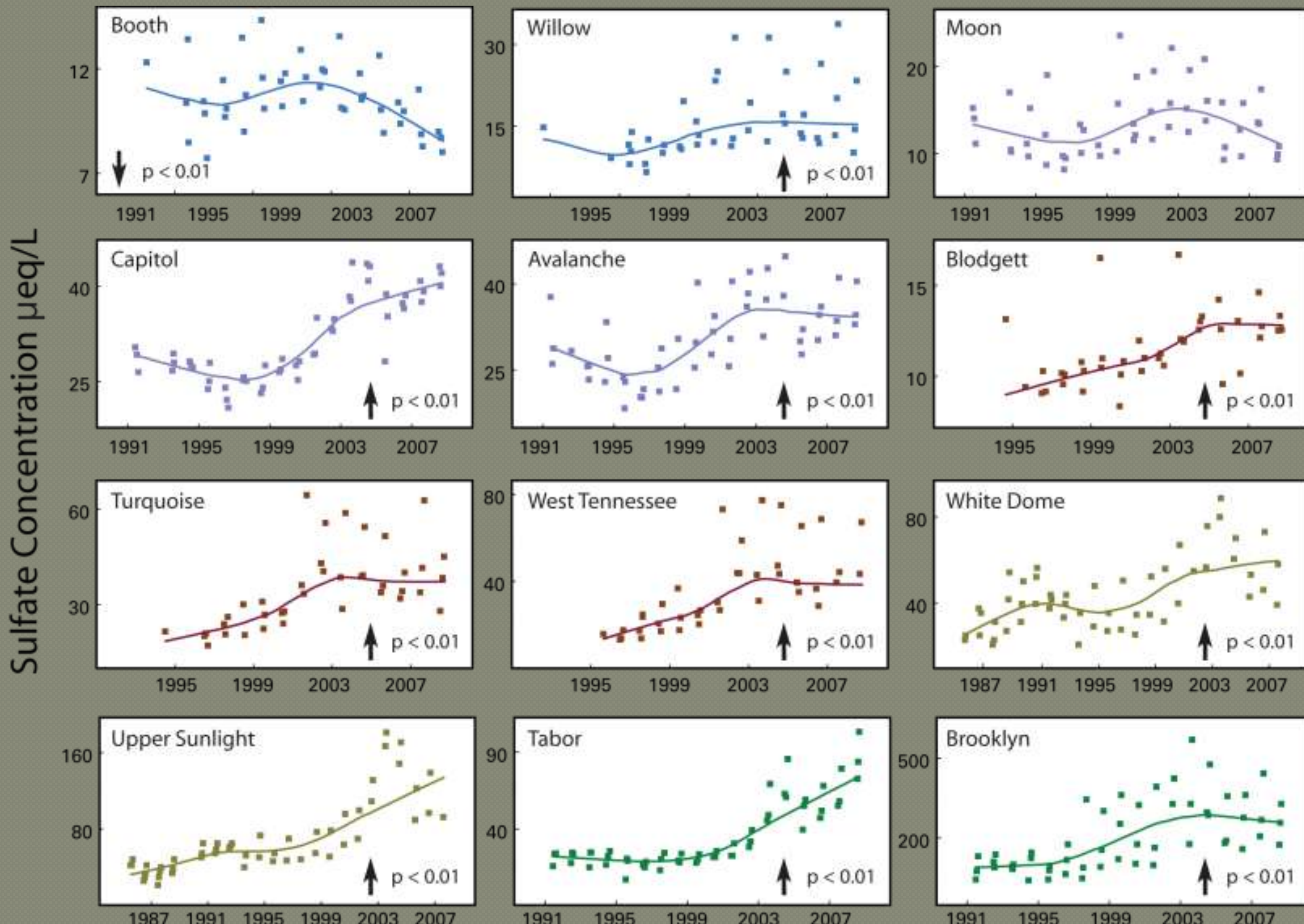
$2H^+$ + SO_4^{-2} + Mg-Exchange Pool ---> Mg^{+2} + SO_4^{-2}

Controls on Lake Sulfate

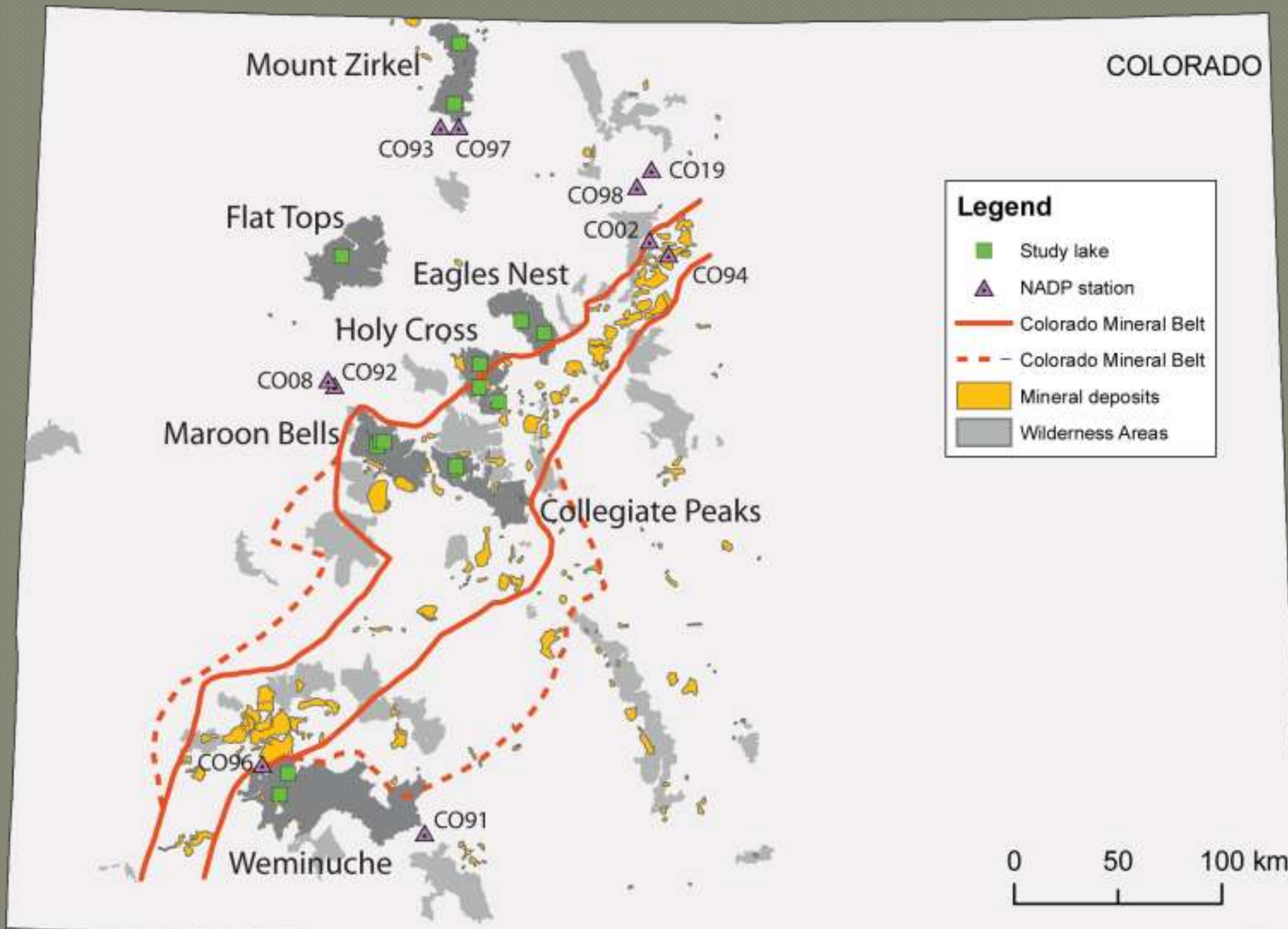
In lakes dominated by atmospheric inputs, sulfate is declining in response to deposition

In lakes dominated by pyrite weathering, sulfate is increasing in response to other factors such as climate?

Pattern is widespread



Spatial correlation to Colorado Mineral Belt



Factors Enhancing the Release of Weathering Products

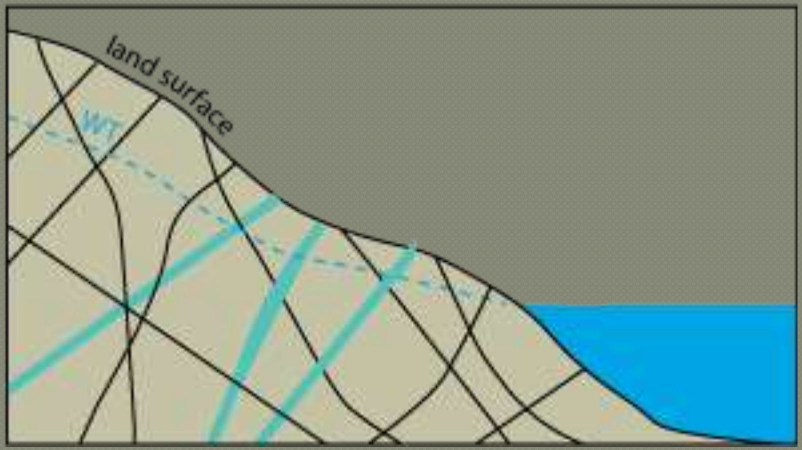
- Precipitation Amount
  - With decreased precipitation, greater contribution of baseflow which would tend to increase concentrations in lakes
  - In Colorado, weak precipitation trends in Sangres and Sawatch, no trends elsewhere in the State
  - Increase in concentrations not uniform among solutes

Factors Enhancing the Release of Weathering Products

- Air Temperature may be playing a role
  - Increases in air temperature observed for all mountainous areas of Colorado
  - Shorter period of snow cover increases exposure of rocks and soils (Sommaruga-Wograth et al. 1997)
  - Melting of permafrost, rock glaciers, and glaciers (Baron et al. 2009, Theis et al. 2007)
  - Reoxidation of reduced sulfur in wetland soils due to lowering of water table caused by increased evaporation (Laudon et al. 2004)

Because pyrite decomposition is dependent on oxygen availability, fluctuating groundwater levels may enhance pyrite oxidation

Silicate weathering would not be affected to same degree



Conceptual Model: An increase in summer air temperatures coupled with earlier snowmelt could increase evaporation and cause the water table to decline

If climate change results in increased summer warming or greater frequency of drought years, sulfate export (metals) from mineralized areas may increase

What about Nitrogen?

- Most study lakes have nitrate concentrations below detection during the growing season
- Only lakes in the Weminuche had sufficient data for trend analysis
- Mid-summer sampling misses the snowmelt period when nitrate is released from snowpack and flushed from soils

Station Name	ANC	Ca	Mg	Na	K	NO_3	Cl	SO_4	SiO_2
Flat Tops Wilderness									
Seven Lakes	↑	○	○	○	○		○	↓	↑
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Summit Lake	↑	↑	↑	○	○		○	↓	↑
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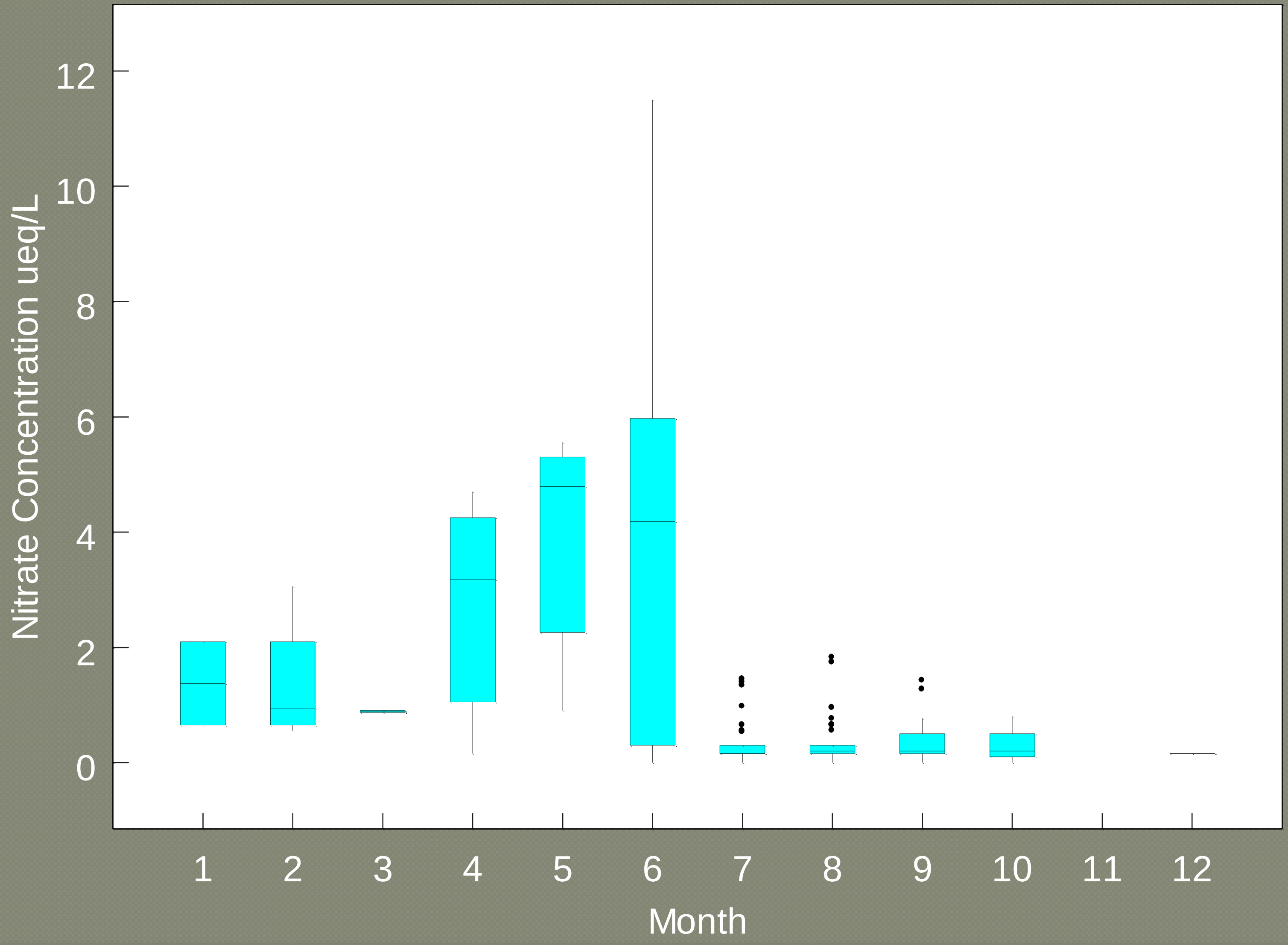
Upper Sunlight Lake	↑	↑	↑	↑	↑	○	○	↑	↑
Upper Grizzly Lake	↑	↑	↑	○	○	○	○	↑	↑

What about Nitrogen?

- Most study lakes have non-detectable nitrate during the growing season
- Only lakes in the Weminuche had sufficient data for trend analysis
- Mid-summer sampling misses the snowmelt period when nitrate is released from snowpack and flushed from soils

Ned Wilson Lake, Flat Tops



Response to climate/deposition is complex

Implications:

- Declining risk of acidification from SO_2 emissions
- Acidification and nitrogen saturation related to NOx emissions
- Enhanced sulfate and possibly metal releases from mined and unmined mineralized areas related to climate change