ACID RAIN

GEOG/ENST 3331 – Lecture 14

Ahrens: Chapter 18; Turco: Chapter 9; A&B: Chapter 14

Beyond the Midterm

Last lecture: Urban Air Quality

- Types of Smog
- NO_x and VOCs
- Ozone and $PM_{2.5}$
- Cigarettes, Formaldehyde and Radon

Update on Expert Panel

Climate Panel

February 23: The Ecofiscal Commission will hold a live-stream event “to dig into the challenges and solutions of coordinating federal and provincial government climate policies”

Moderator: Chris Ragan: Chair of Canada's Ecofiscal Commission and McGill University, Department of Economics

Expert Panel Members

- Paul Boothe: Director, Lawrence National Centre for Policy & Management, Western University
- Stewart Elgie: Professor of law and economics, University of Ottawa, and director of the interdisciplinary Environment Institute
- Kathryn Harrison: Professor of Political Science, UBC
- Jennifer Winter: Associate Director, Energy and Environmental Policy, Asst. Professor, The School of Public Policy, University of Calgary

Federal and provincial ministers will be meeting on March 3rd to discuss how best to move forward with coherent climate policies.

Assignment 6

- What are possible positive *and* negative effects of an increased NO_x flux into the atmosphere?
- Describe four processes that contribute to the dispersal of pollutants in the atmosphere. In what ways do taller chimneys or smokestacks contribute to reducing the impact of air pollution?

Air Quality Index (Ontario)

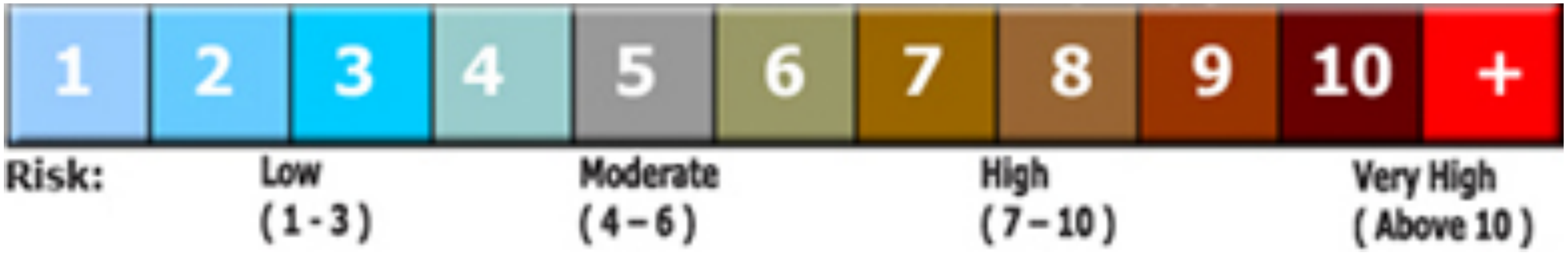
- http://www.airqualityontario.com/science/background.php
- Levels of six contaminants are monitored
  - Ozone
  - Fine particulate matter
  - Nitrogen dioxide
  - Sulphur dioxide
  - Carbon monoxide
  - Total reduced sulphur compounds

Air Quality Index (Ontario)

- Each contaminant is assigned an index number based on concentration and potential health impact
- The *worst individual* contaminant index is used as the Air Quality Index
- Scale ranges from 0-100+

Air Quality Health Index (Canada)

- New (2005) from Environment Canada
- A function of O_3, $PM_{2.5}$, and NO_2 concentrations
- Scale from 1 to 10+



Acid Rain – lecture objectives

- **Understand the chemistry of acid rain**
- **Detail the impacts of acid rain, including dispersal patterns and critical loads**
- **Review mitigation measures**

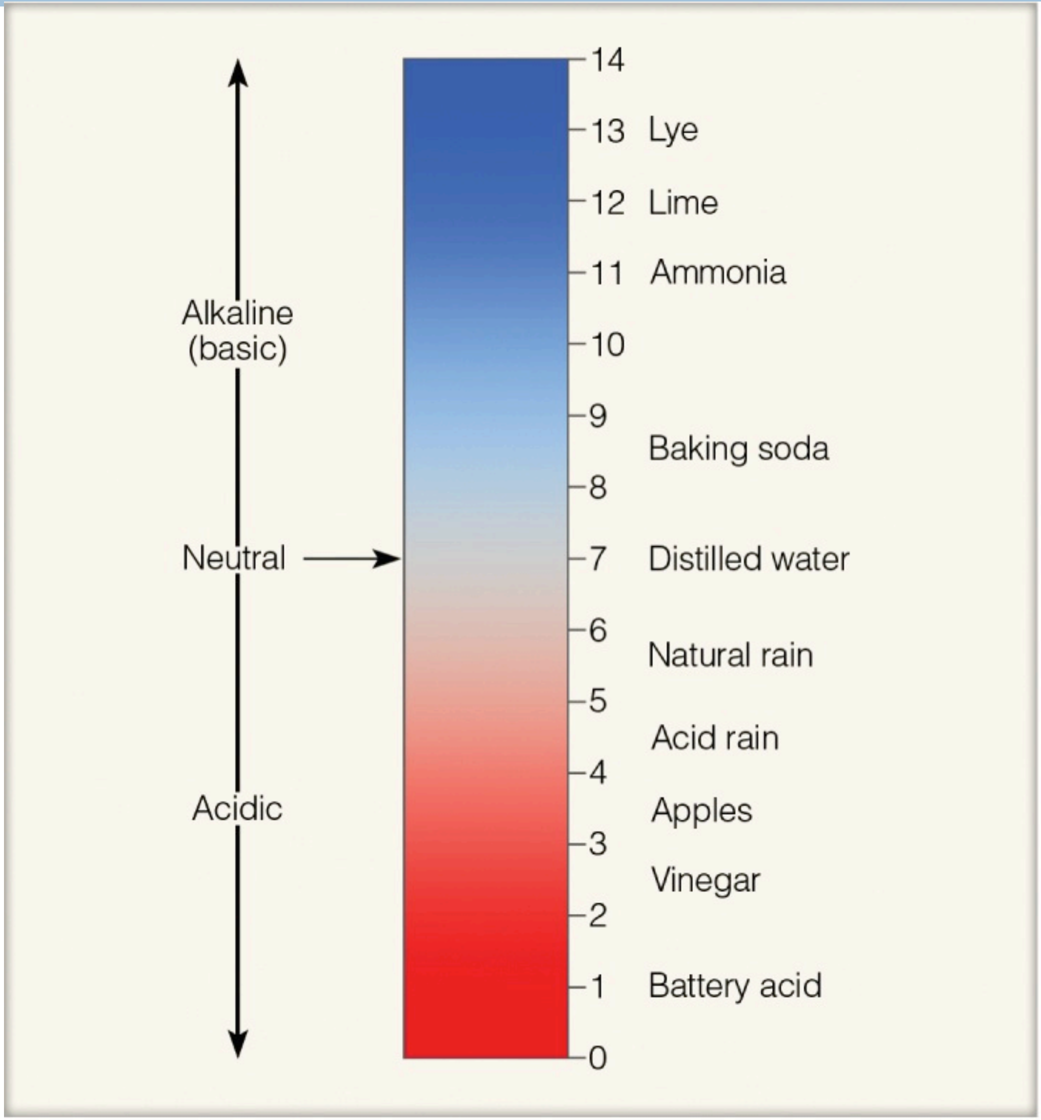
Acidity

- A measure of amount of H^+ radicals in a solution.
  - Radicals are very reactive
  - Powerful acids will react with and dissolve many substances.
- Water (H_2O) normally includes a very small amount of radicals
  - H^+ (acidic)
  - OH^- (basic)

$$H_2O \leftrightarrow H^+ + OH^-$$

pH – a measure of concentration

- pH is a logarithmic scale
- pH of 1 means a concentration of 10^{-1}
  - or one in 10.
- pH of 7 means H^+ concentration of 10^{-7}
  - one in every 10,000,000 particles.
- pH of 7 is neutral



Ahrens: Fig. 18.20

Rain: Carbonic acid

- Rain forms from droplets of water suspended in the air; other substances dissolve into the water.
  - "Natural rain" is slightly acidic with a pH of 5.6.

- CO_2 in the atmosphere can react with water to form *carbonic acid*

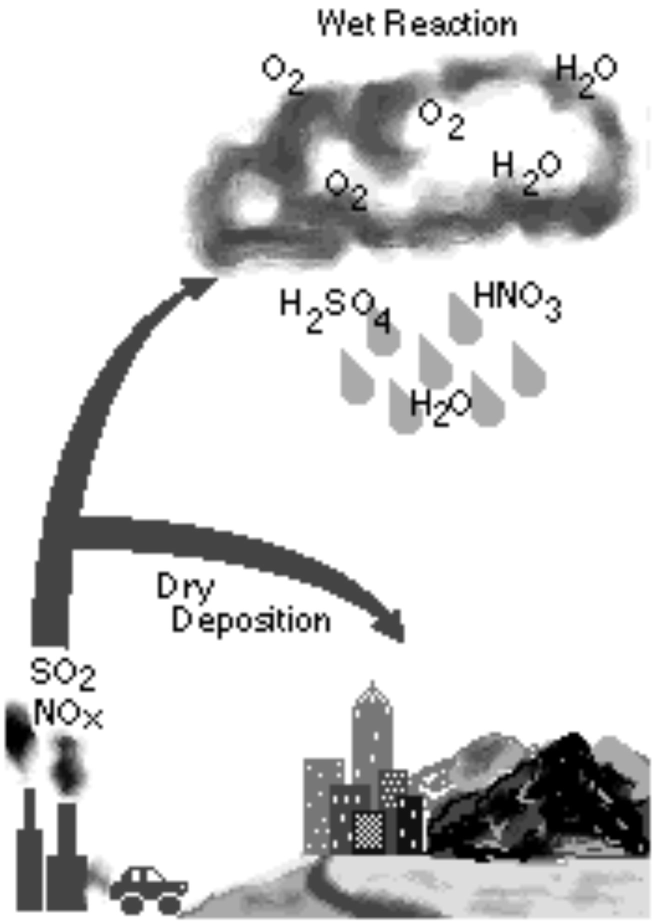
$$CO_2 + H_2O \rightarrow H_2CO_3$$

- Carbonic acid is a weak acid; a small amount of it dissociates in water:

$$H_2CO_3 \leftrightarrow CO_3^{2-} + 2H^+$$

Acid rain

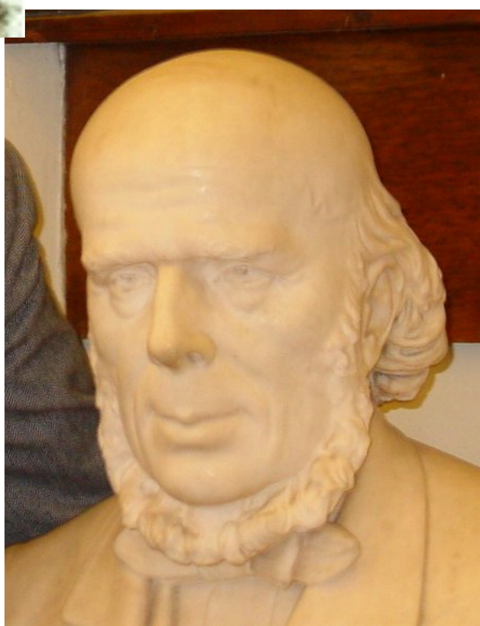
- Rain below pH 5.0
- Sulfuric acid (62%)
  - H_2SO_4
- Nitric acid (32%)
  - HNO_3
- Hydrochloric acid (6%)
  - HCl



History of Acid Rain

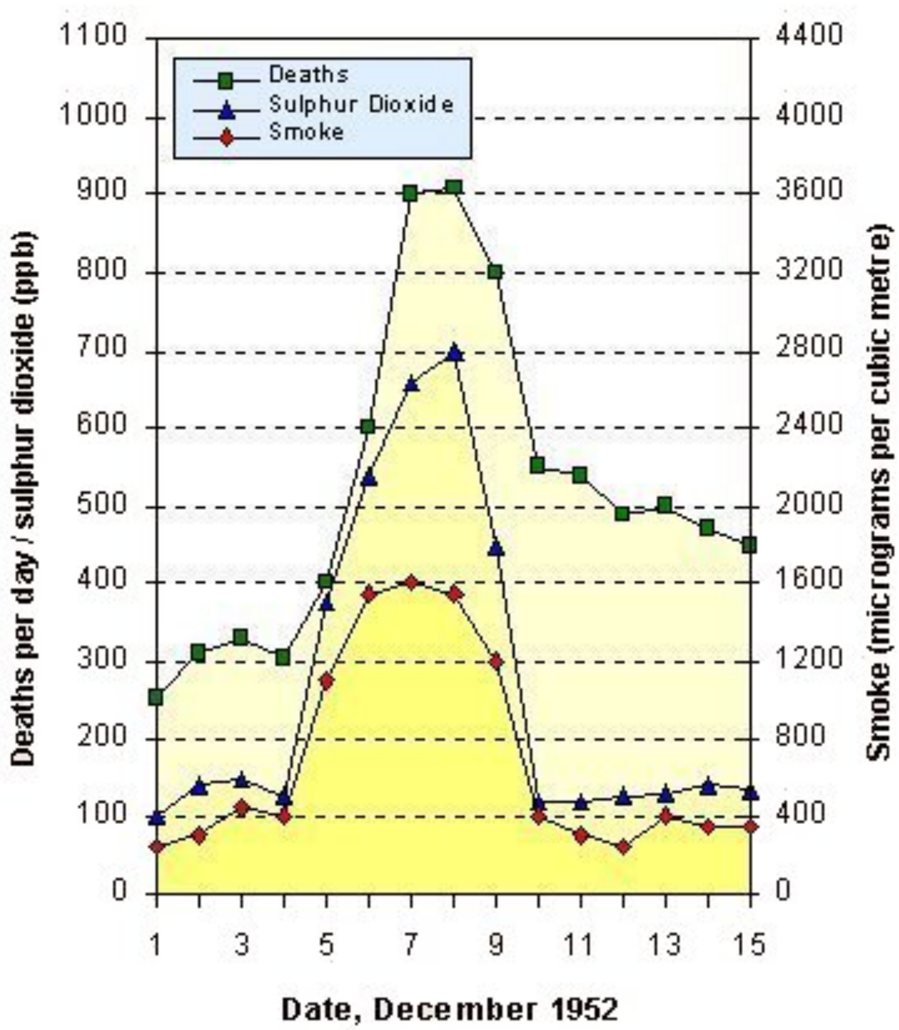
- Pliny the Elder (25-79 AD)
- 1872 – *Air and Rain*
  - Robert Angus Smith, England
  - Damaged vegetation, bleached fabric, corroded metal
- 1950s – linked to urban air emissions
- 1970s - major monitoring and research efforts.

Pliny



Robert Angus Smith

The Great London Smog



Anthropogenic Emissions

Pollutant	*Full Name*
CO	Carbon Monoxide
SO_x	Sulfur oxides
NO_x	Nitrogen oxides
VOCs	Volatile organic compounds
PM	Particulate matter

Primary Pollutants

Sulfur oxides and nitrogen oxides are acid rain precursors, i.e. in the presence of water, they form an acid.

Sulfur oxides: Sulfuric acid

$$SO_x \xrightarrow{H_2O} H_2SO_4$$

$$H_2SO_4 \leftrightarrow SO_4^{2-} + 2H^+$$

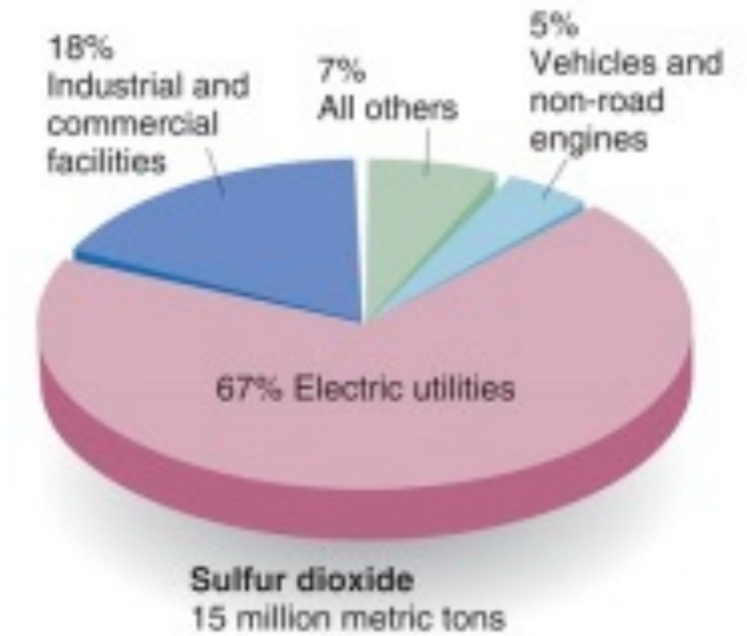
Sources

- Coal burning
  - Power plants
- Smelters
- Pulp milling

Mainly stationary sources

A&B: Fig. 14.4

Sources of SO_x

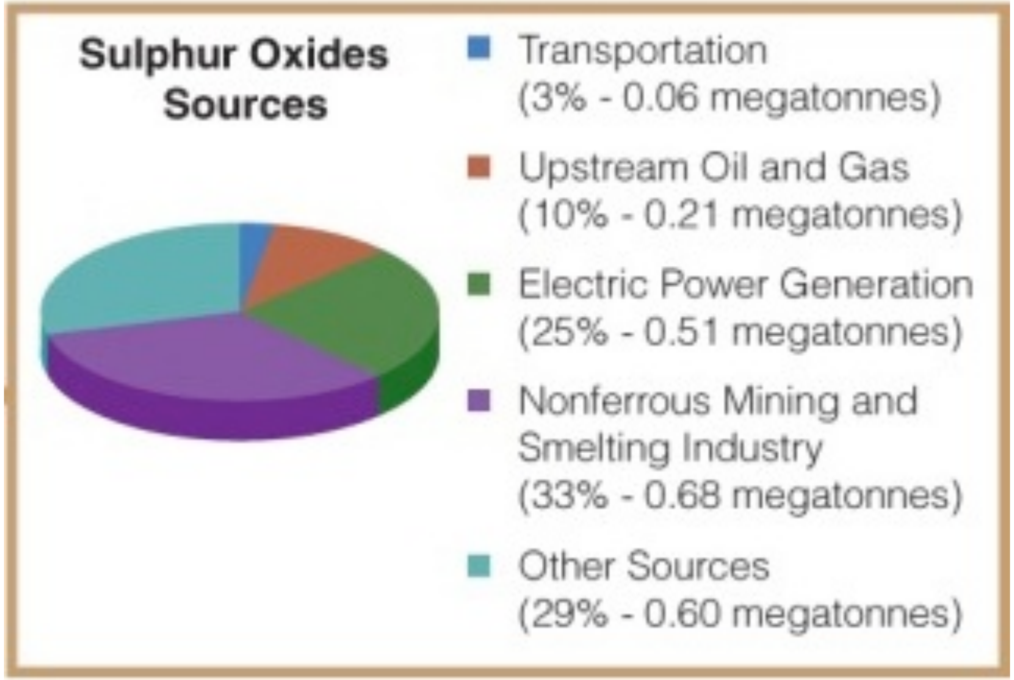


A&B: Fig. 14.1

- US
  - Mainly electrical utilities

Sources of SO_x

- Canada
  - Mainly industrial



Ahrens: Fig. 18.2

Nitrogen oxides: Nitric acid

$$NO_x \xrightarrow{H_2O} HNO_3$$

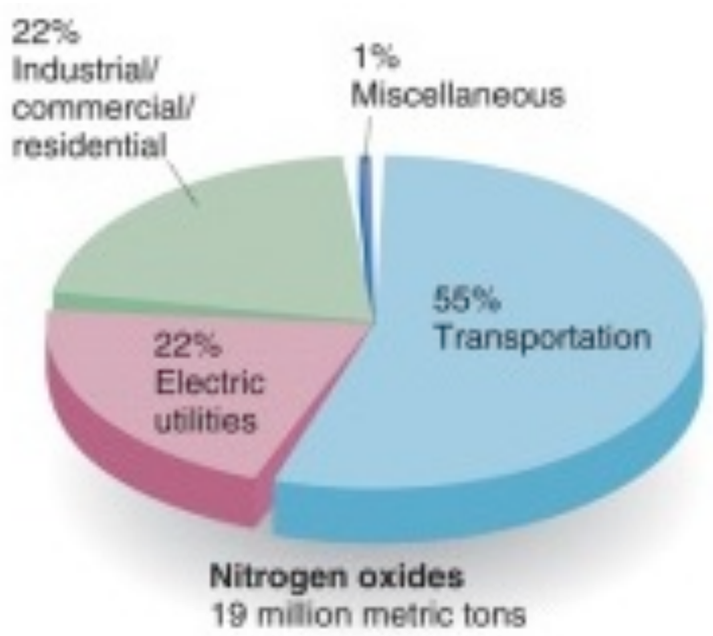
$$HNO_3 \leftrightarrow NO_3^- + H^+$$

Sources

- Fossil fuel consumption
- Forest fires

Image: ORNL

Sources of NO_x

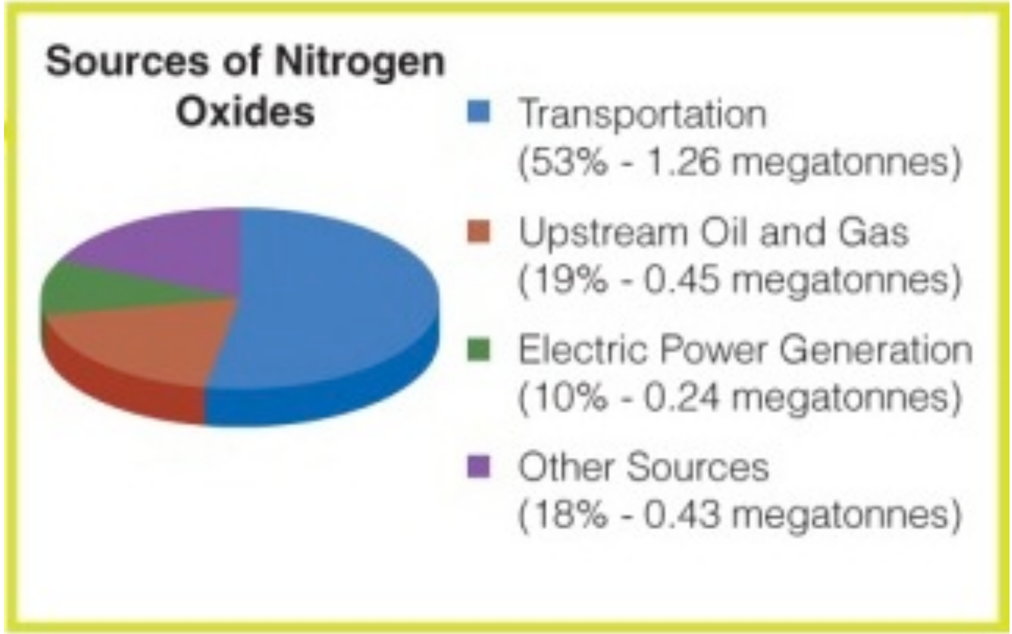


A&B: Fig. 14.1

- US
  - Mainly vehicles

Sources of NO_x

- Canada
  - Same



Ahrens: Fig. 18.2

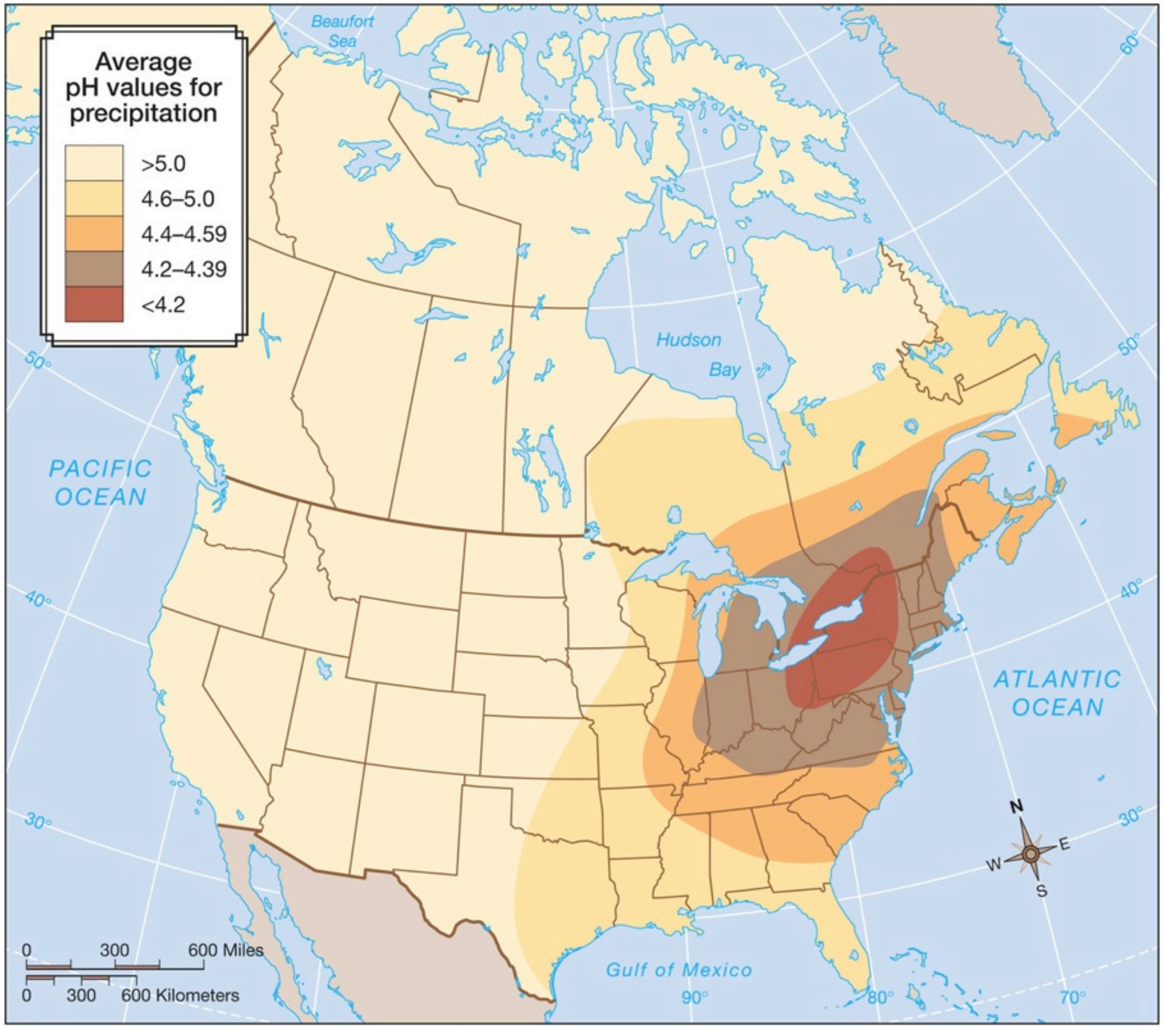
Where is it?

Industrial heartland

Eastern North America

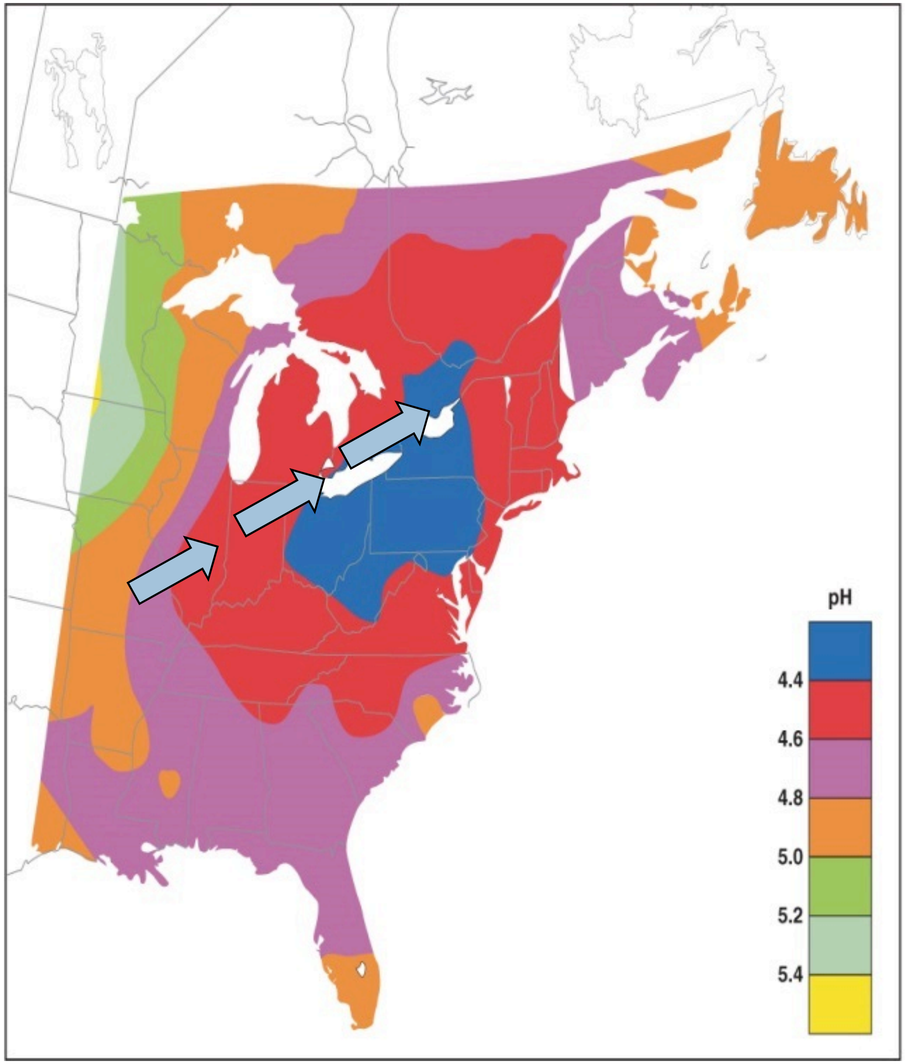
Prevailing wind?

A&B: Figure 14-3



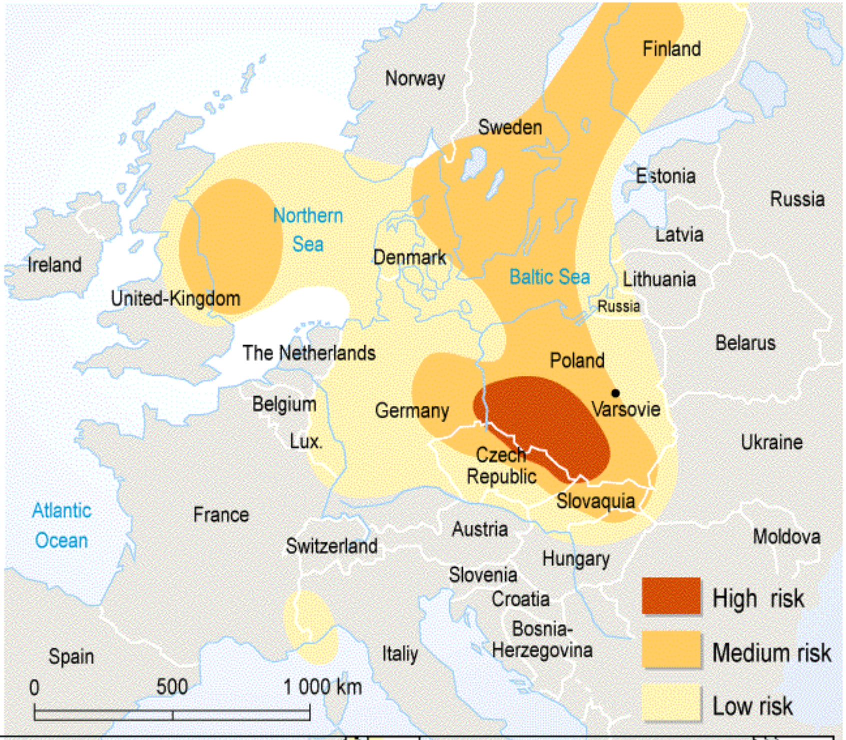
Long range transport

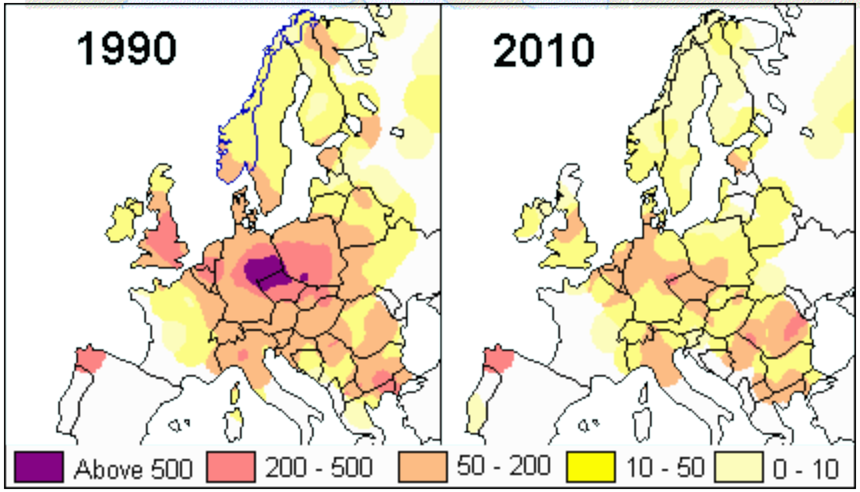
- In Ontario, 50% of acid rain precursors originate in the US
  - SO_x, NO_x
- 10% of acid rain falling in US originated in Canada.



Western Europe

- Acid rain risk
- What is the prevailing wind?





Source: UNEP, 1998

Tonnes/km^2

‘Plume’ versus ‘Pool’

Two theoretical constructs

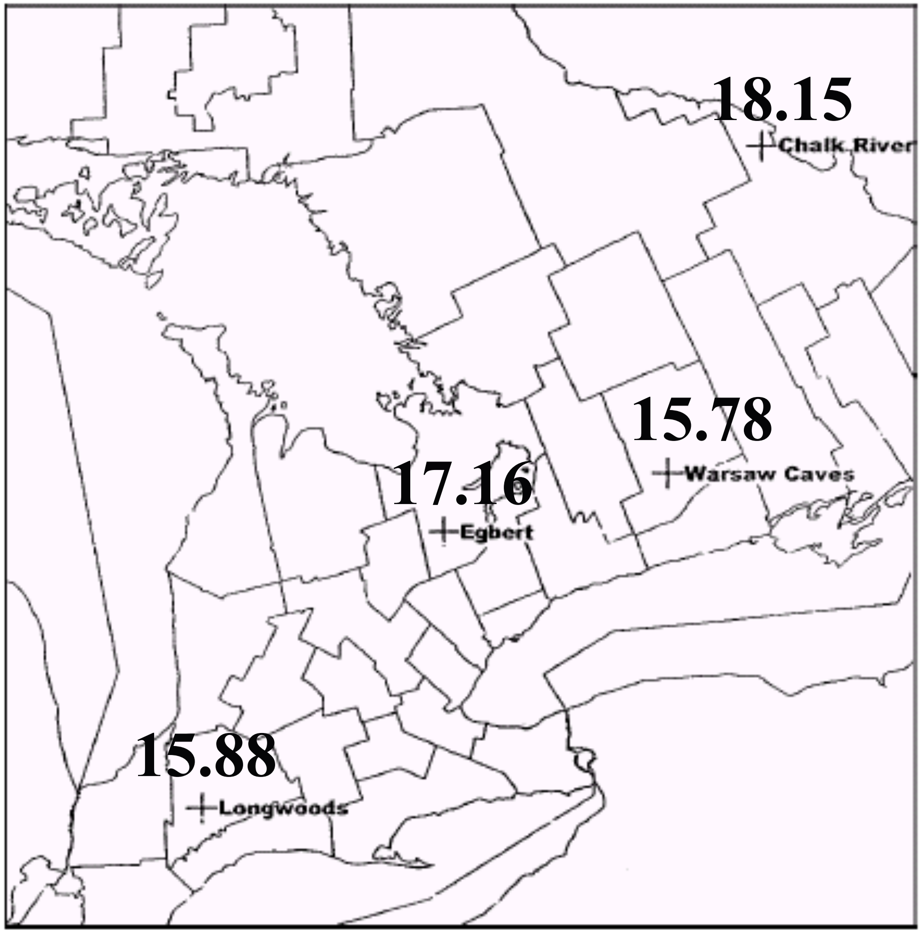
A. Plume model: active transport of air away from source region – rain event washes out air but air is replaced by moving plume of acid laden air

B. Pool (or slower plume) model: rain event depletes acid content which is not fully replaced thus subsequent rain events have a lower concentration of acid

Acid rain in SW Ontario

- Summer precipitation at four sites
  - Relatively uniform
- Deposition? How much acid rain pollutant falls at these locations?

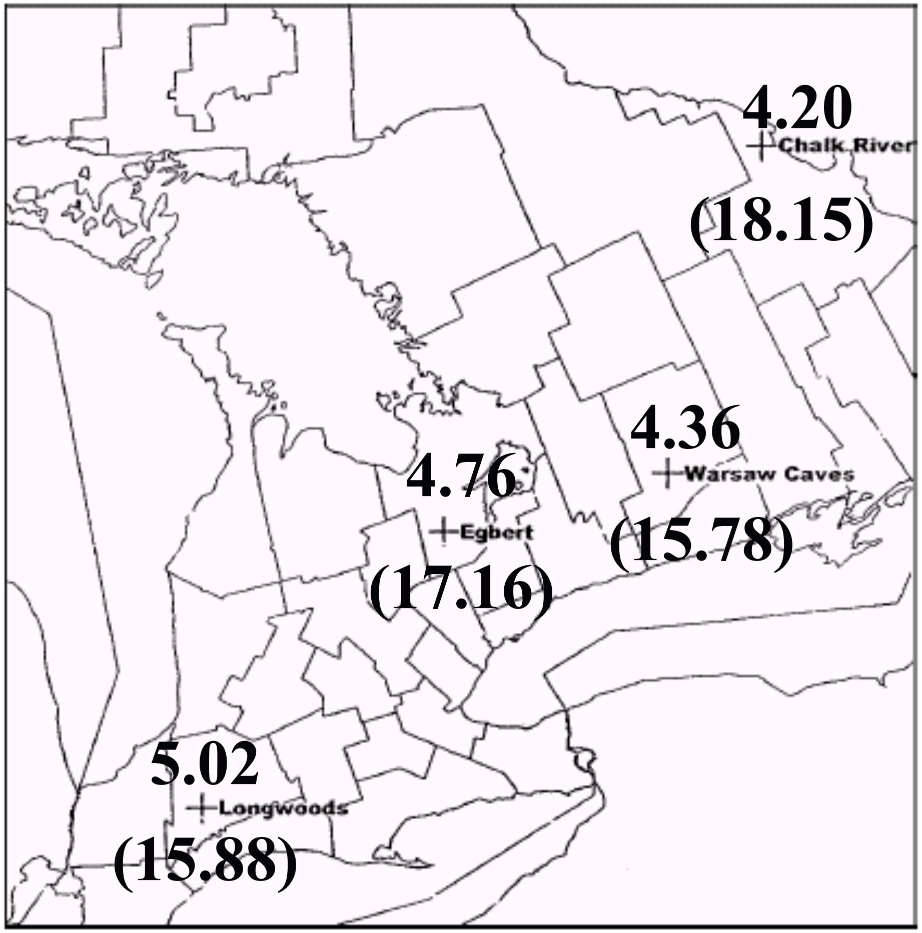
Precipitation (cm)



Sulfate deposition

- Does not follow the precipitation pattern
- Deposition decreases to the northeast
  - Prevailing wind
  - Distance from source of pollutant

Deposition (kg/ha) - Sulfate

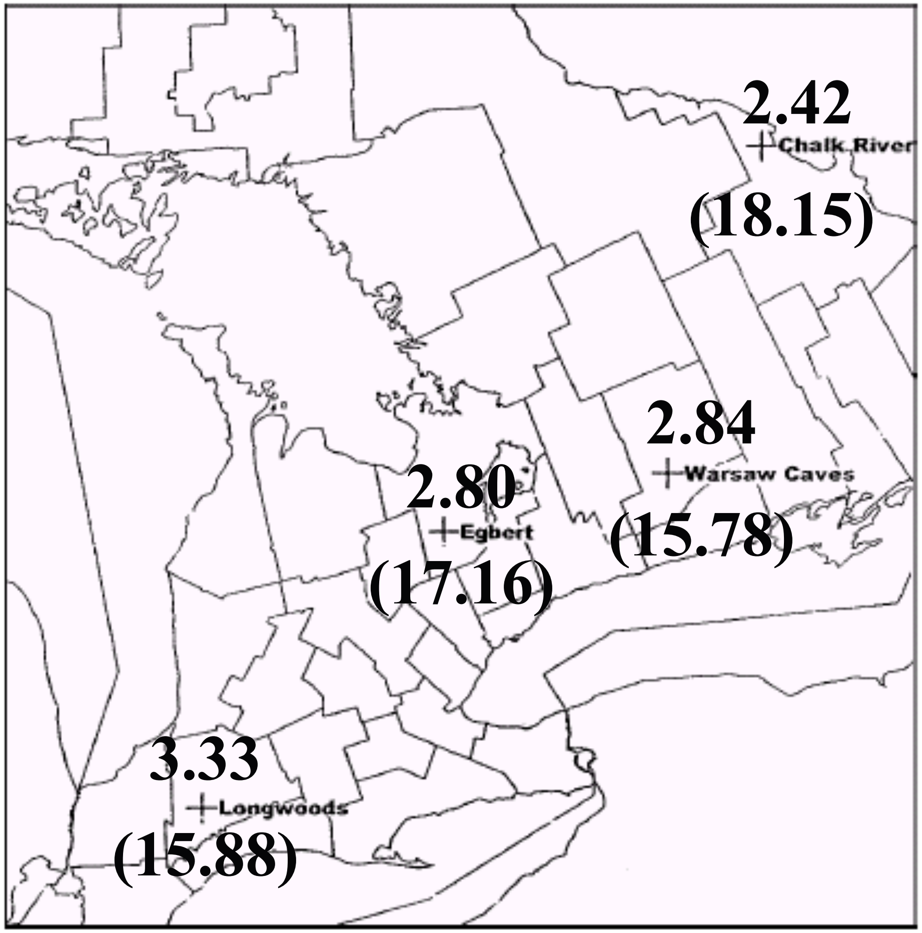


Sulfate concentration

- Generally a reduction of concentration to the northeast as expected

- Warsaw Caves has higher concentration but less deposition than Egbert
- (Less rainfall at Warsaw Caves than Egbert)

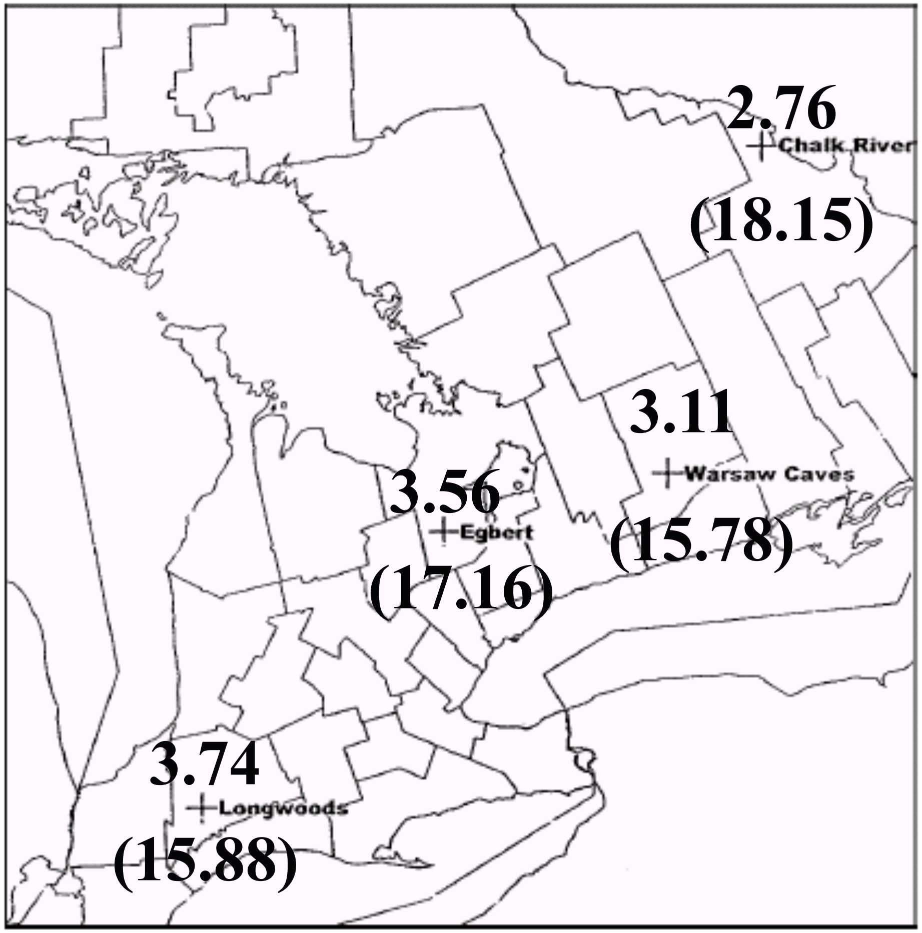
Concentration mg/L - Sulfate



Nitrate deposition

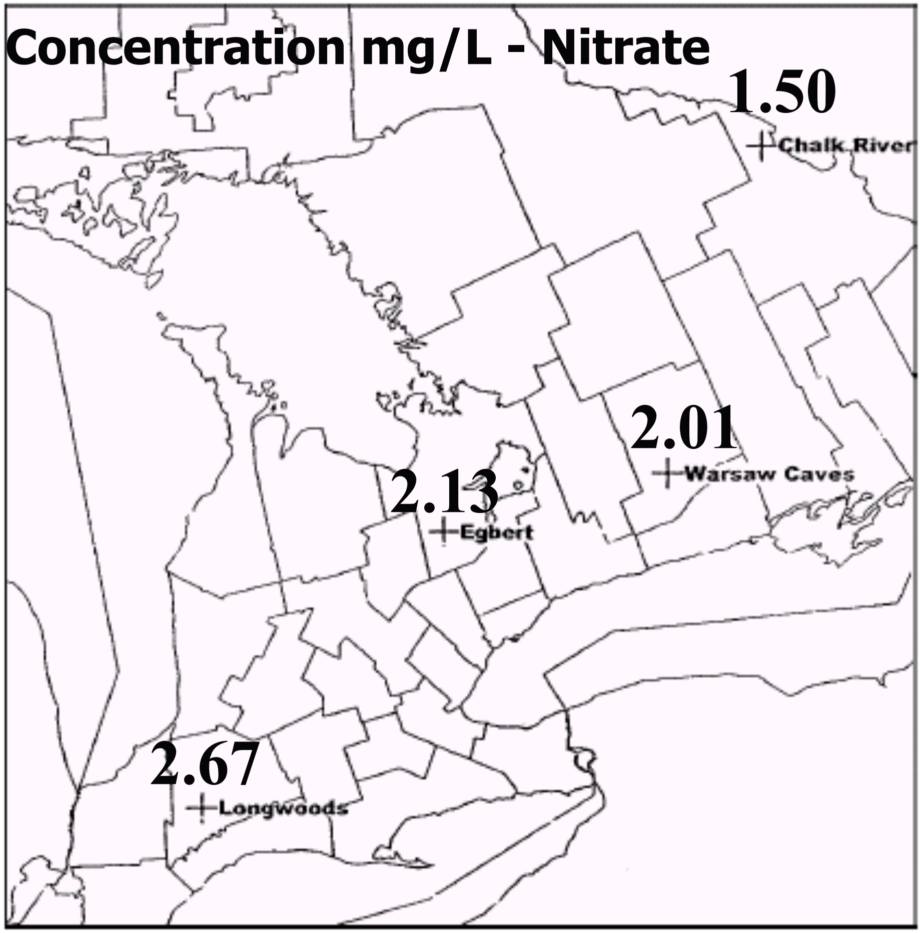
- Deposition decreases uniformly to the northeast
- Since precipitation does not, it must mean concentration does
  - Prevailing wind
  - Pollutant source

Deposition kg/ha - Nitrate



Nitrate concentration

- Decrease in nitrate concentration – northeasterly direction
- Similar but not identical to sulfates
  - What's happening at Warsaw Caves?
- Suggests that nitrates and sulfates do not behave identically



‘Plume’ versus ‘Pool”

Back to ‘plume’ versus ‘pool’

How do we tease out the difference?

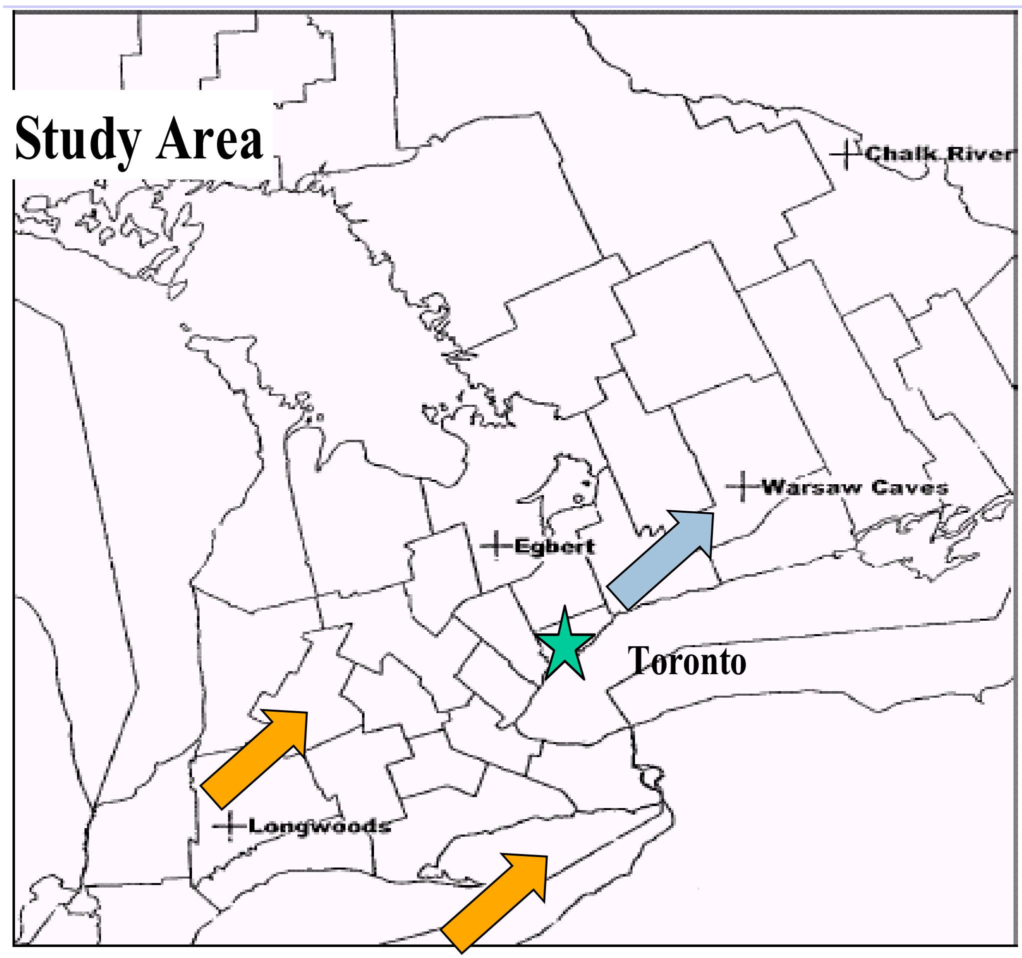
- Multiple regression of deposition with concentration and precipitation
- If deposition is well correlated with precipitation – **plume**
- If concentration is well correlated with precipitation (and not deposition with precipitation) – **pool**

Acid rain – SW Ontario

- Statistical analysis
  - Correlation supports idea of a plume for most circumstances (deposition mainly dependent on precipitation)
  - 1992 identified as an outlier year – excessive rainfall – pool model works better
  - Anomaly at Warsaw Caves

Warsaw Caves

- In 1992 at Warsaw Caves, the precipitation was high, this led to a decrease in nitrate concentration but not sulfate concentration
- Why? and why did this not happen at Egbert?
- Likely explanation, point source upstream in GTA
  - Lakeview Power Plant



Acid Rain – SW Ontario

Conclusions

- Deposition decreases in a NE direction, away from source region
- Plume model works best
  - Except in extreme rainfall years
- Warsaw Caves data indicates an upstream sulfate source - especially apparent in heavy rainfall years - likely the coal burning electrical plant in the GTA

Impacts of Acid Rain

Damage to plants

- Damage to leaves
- Leaching of nutrients

Lake acidification & aquatic life

- Altered pH
- Mobilization of toxins

Buildings

- Dissolving limestone, etc.

Water Quality

Trees

Acid rain affects trees directly by impacts on leaves

Acid rain also removes nutrients such as calcium (Ca), sodium (Na) and magnesium (Mg) from the soil, indirectly causing crown dieback.

Ahrens: Fig. 18.23

Crown dieback

Due to soil nutrient depletion, tops of trees starve and the crown dies off.

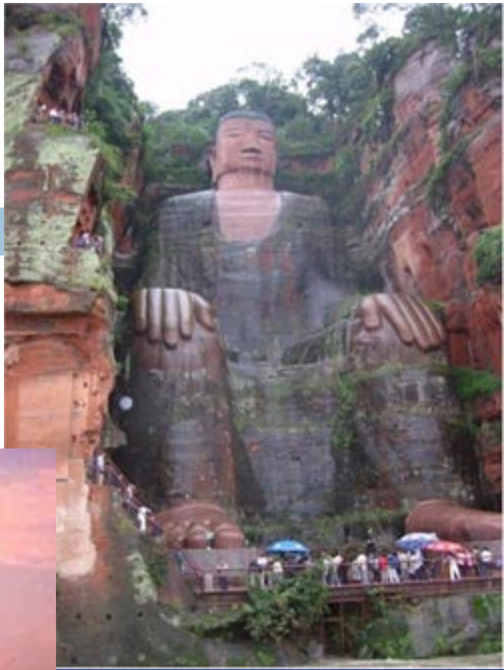
Acid rain and aquatic life

As water pH approaches	**Effects**
6.0	•crustaceans, insects, and some plankton species begin to disappear.
5.0	•major changes in the makeup of the plankton community. •less desirable species of mosses and plankton may begin to invade. •progressive loss of some fish populations is likely
Less than 5.0	•the water is largely devoid of fish. •the bottom is covered with undecayed material. •the near-shore areas may be dominated by mosses. •terrestrial animals dependent on aquatic ecosystems, e.g. waterfowl, are affected.

Source: Environment Canada

Acid rain impact on buildings

- Acid rain converts marble and limestone ($CaCO_3$) to a soluble form (e.g. $CaSO_4$)
  - Washes away



Leshan Giant Buddha, Sichuan, China

Taj Mahal

Parliament Buildings Ottawa, Canada

Acid rain and human health

- Dissolves toxins into drinking water
  - Thallium in Ukraine
  - Lead, aluminum, arsenic, cadmium, selenium
    - *Bioaccumulation*
- Acid smog
  - Respiratory ailments

Emission Reduction

1985

- Governments of Canada and seven eastern provinces enacted a program to reduce SO_2 emissions by half by 1994
- Done successfully (SO_2 emissions 54% lower by 1994)

However, 50% of acid rain comes from US

1991

- US/Canada Air Quality Agreement to reduce SO_2 emissions

1996

- 27% reduction in US emissions, 40% by 2010
- Area in Canada receiving 20 kg/ha/yr declined by 61%.

Are lakes recovering?

Of 202 lakes studied:

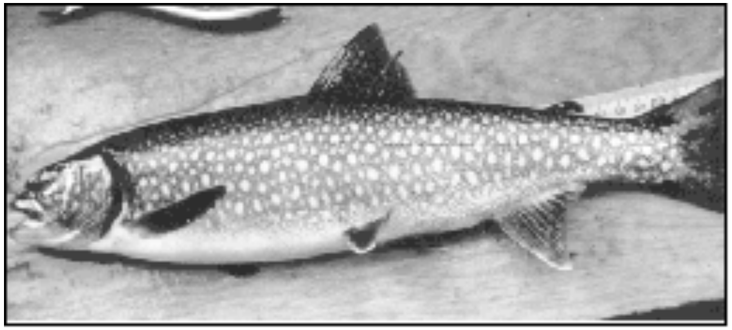
- 33% reduced levels of acidity
- 56% show no change
- 11% more acidic
- Substantial recovery in Sudbury region
- Least improvement was in the Atlantic region.

Soil buffering

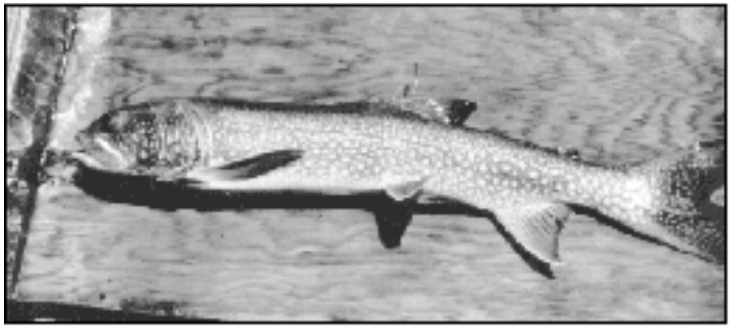
- Different soil types react differently to acid deposition
- Alkaline “buffers”:
  - NH_4OH
    - $NH_3 + H_2O \rightarrow NH_4OH$
    - $NH_4OH \leftrightarrow NH_4 + OH$
    - $OH + H \rightarrow H_2O$
  - NaOH
  - $Ca(OH)_2$

Acid rain impact on fish

- 1979



- 1983



- 1984

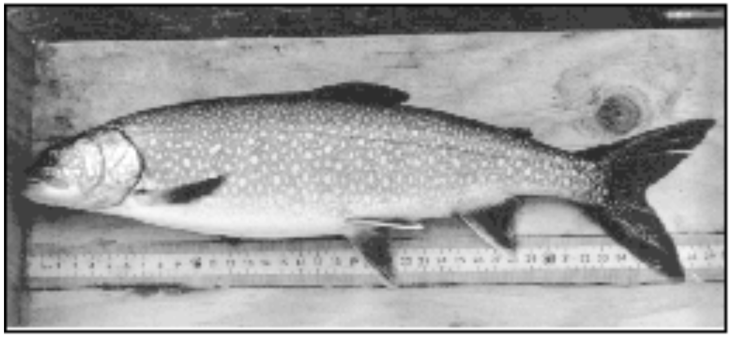
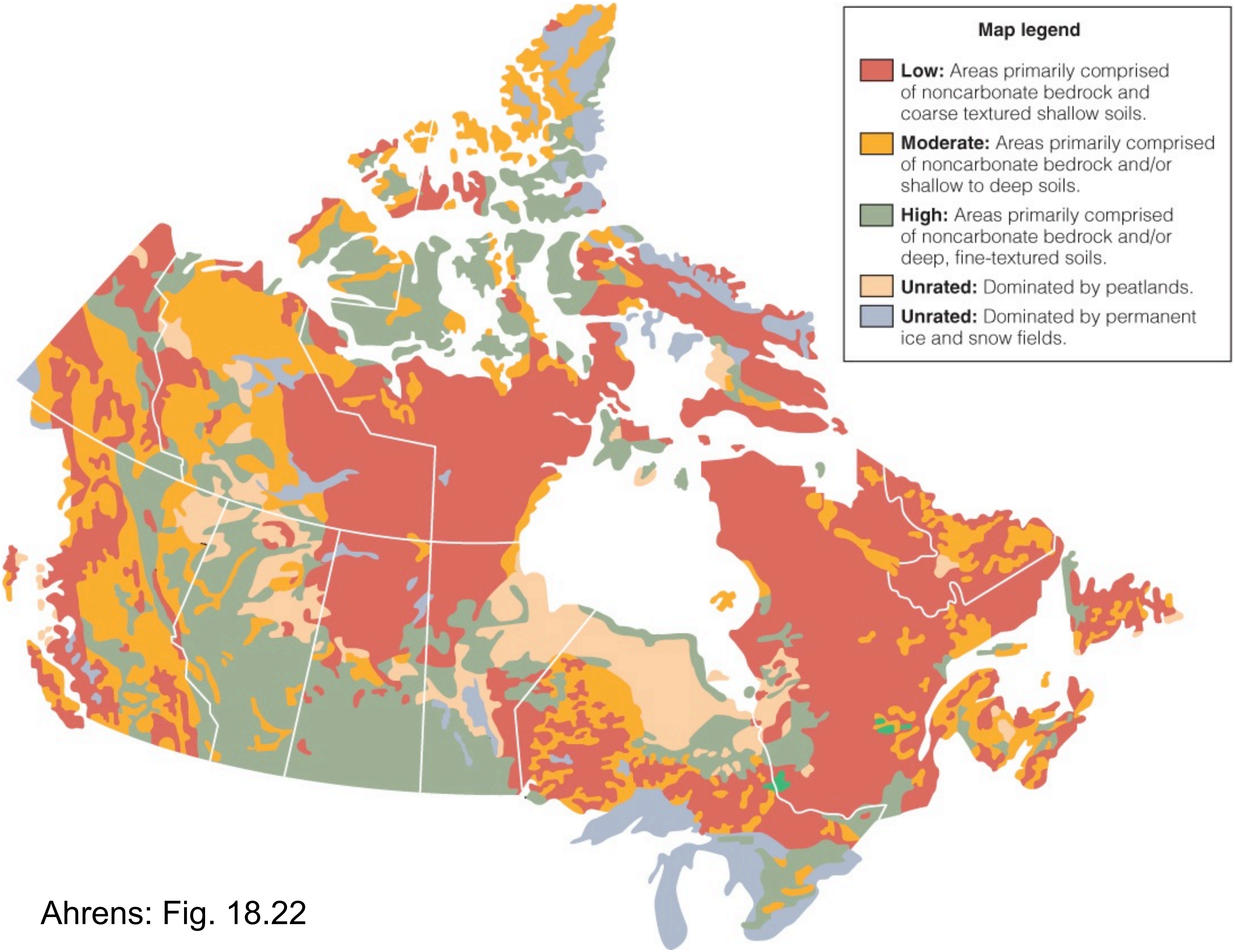


Image: Government of Canada

Soil buffering

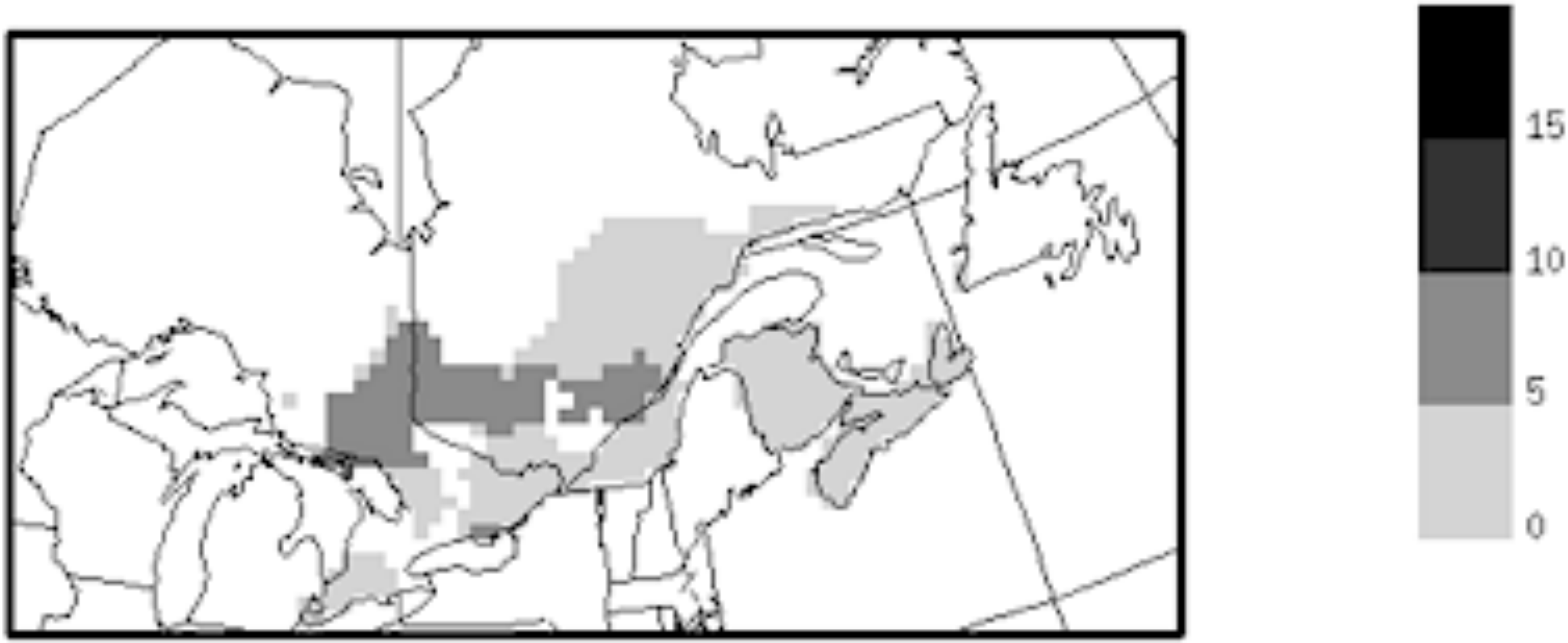
Traditionally mitigation efforts have used deposition rates for reduction targets

- However, soil types with lots of buffering compounds are less vulnerable to acid rain
- Lakes in Canadian Shield are typically *not* well-buffered



Ahrens: Fig. 18.22

Exceeding Critical Loads



Critical load excess projected for 2010 in kg/ha/yr.

Emission Reduction

1998 Canada-wide acid rain strategy

- further reductions in SO_x emissions
- improved monitoring of acid rain and its effects
- no specific plan for NO_x reduction.

- Good progress, but not solved

Next lecture

- Pollution in the Arctic