Compounding Benefits of Air Pollution Control

A Revised View of Air Pollution Economics

Amanda J. Pappin, Amir Hakami --- Carleton University

Philip Blagden, Masoud Nasari, Mieczyslaw Szyszkowicz, Richard T. Burnett --- Health Canada

Applying Epidemiology in Health Impact Assessment

Integrate risk estimates from epidemiological studies with air quality models to estimate

- The distribution of health impacts (affected populations), or

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- The distribution of health impacts (affected populations), or
- **Source attribution of health impacts (emissions responsible)**

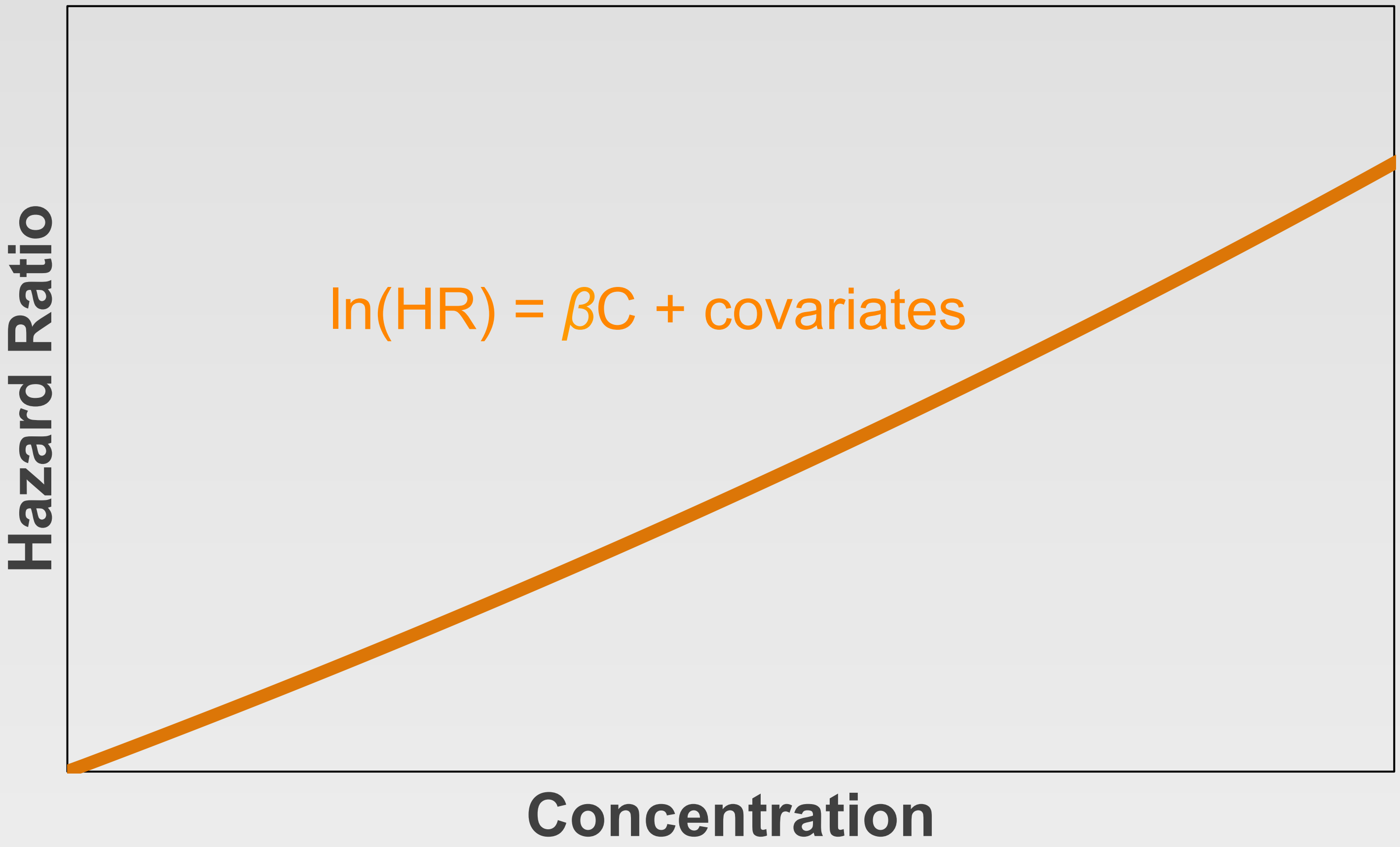
Identifying Sources of Health Impacts

$$\frac{\Delta \$}{\Delta \text{Emissions}} = \underbrace{\frac{\Delta \$}{\Delta \text{Mortality}}}_{\text{Economics}} \times \underbrace{\frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}}}_{\text{Epidemiology}} \times \underbrace{\frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}}_{\text{Air quality modeling}}$$

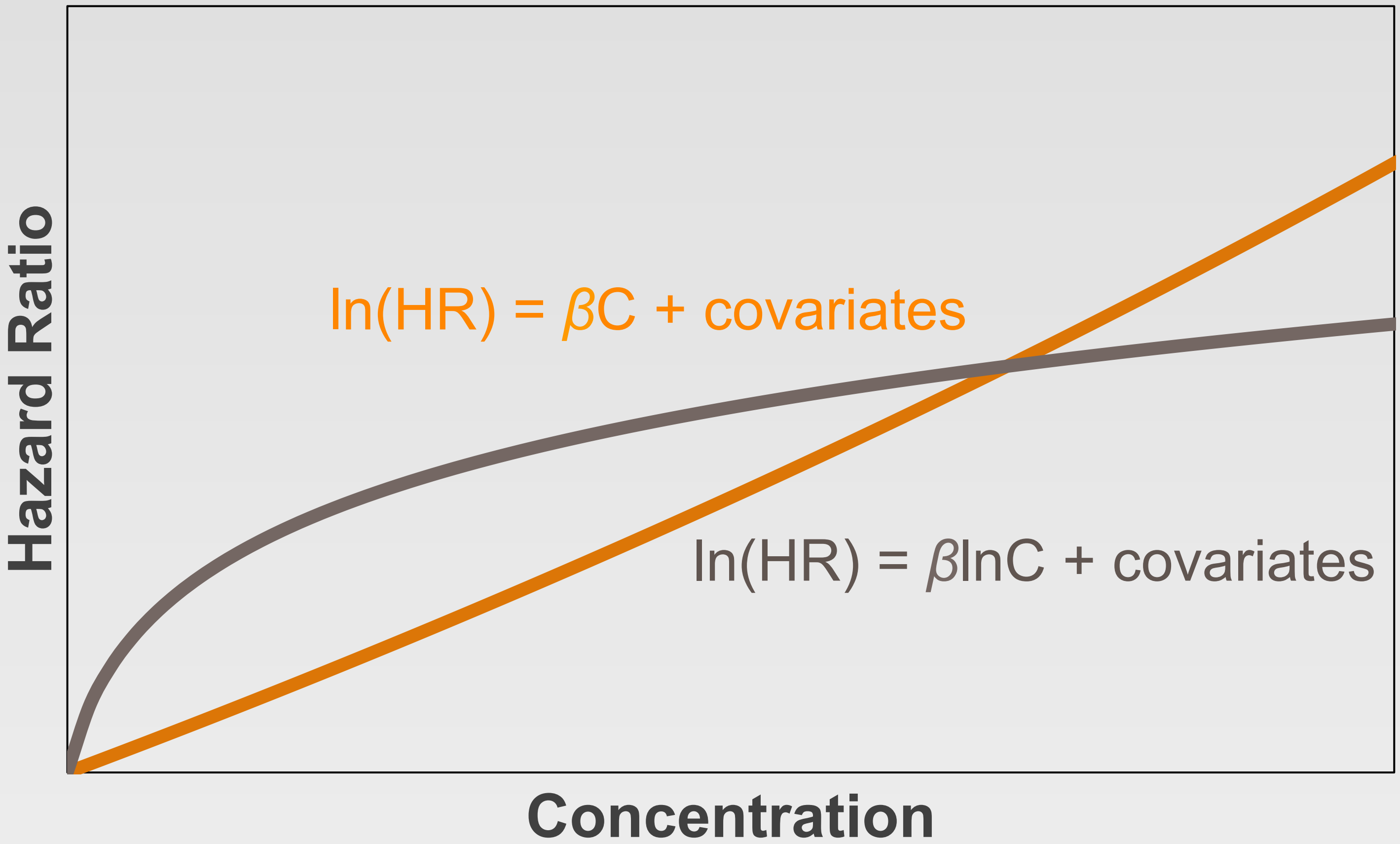
Monetized benefits

-- per-ton basis (benefits-per-ton or marginal benefit)

Traditional Linear CRF



Linear vs Log-linear CRFs



Traditional Health Impact Function

$$M(\$) = M_0 \, Pop(1-e^{-\beta C})V_{SL}$$

Mortality rate and population

Derived from the CRF --- best model fit for O_3 and mortality in Canada

Value of statistical life

Revised Health Impact Function

$$M(C) = M_0 \, Pop(1 - e^{-\beta \ln C}) V_{SL}$$

Mortality rate and population

Derived from the CRF --- best fits for NO_2 and $PM_{2.5}$ in Canada

Value of statistical life

Nonlinearity in Sensitivities

$$\frac{\Delta \$}{\Delta \text{Emissions}} = \frac{\Delta \$}{\Delta \text{Mortality}} \times \frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}} \times \frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}$$

Monetized benefits

Economics

Epidemiology

Air quality modeling

Nonlinearity in Sensitivities

$$\frac{\Delta \$}{\Delta \text{Emissions}} = \underbrace{\frac{\Delta \$}{\Delta \text{Mortality}}}_{\text{Economics}} \times \underbrace{\frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}}}_{\text{Epidemiology}} \times \underbrace{\frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}}_{\text{Air quality modeling}}$$

Monetized benefits

Economics

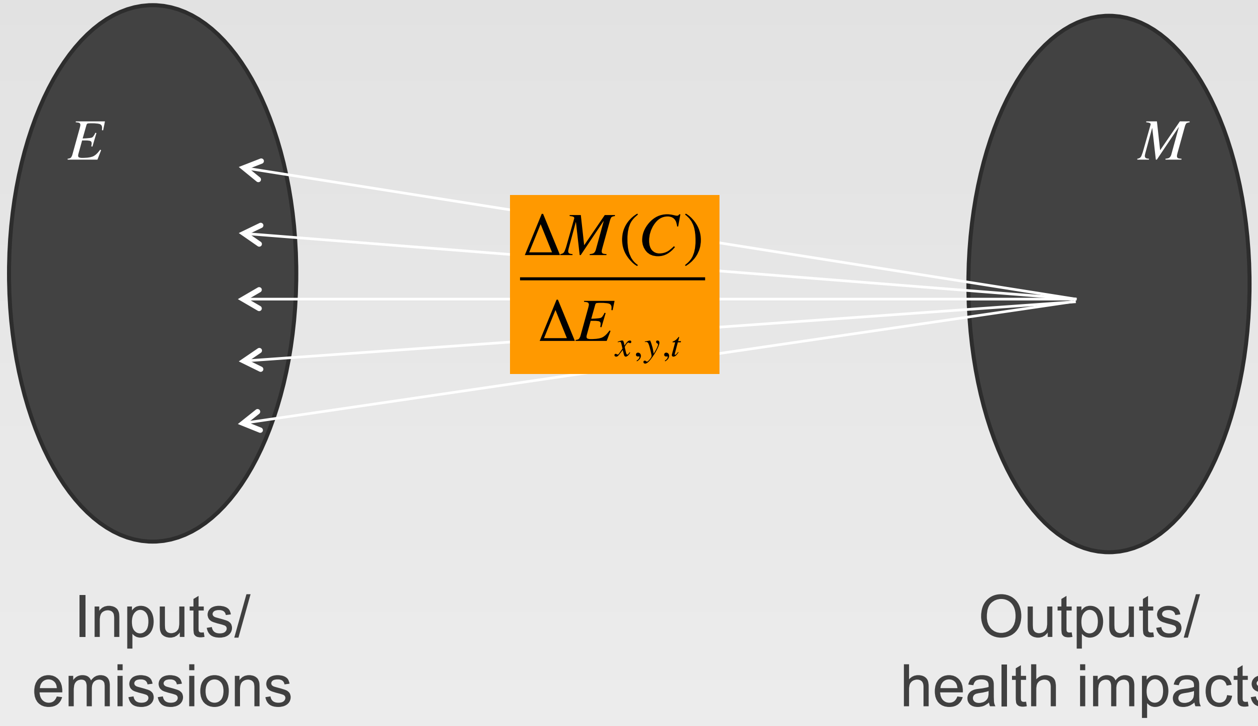
Epidemiology

Air quality modeling

Adjoint Air Quality Modeling

Tracing **mortality** backwards to emissions:

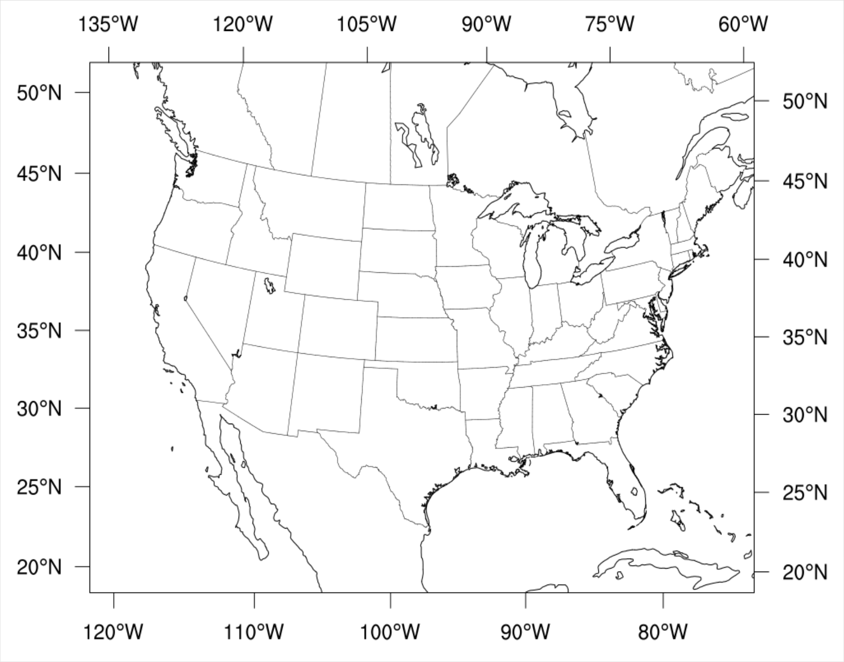
where influences come from (Pappin and Hakami, 2013).



Case Study

CMAQ-Adjoint

- May-Sept 2007
- 36 km resolution
- SAPRC99



Case Study

Cost Function, J = monetized non-accidental mortality in Canada attributable to

- Long-term O_3 exposure
- Long-term NO_2 exposure

Canadian Epidemiological Data (Crouse et al. EHP 2015)

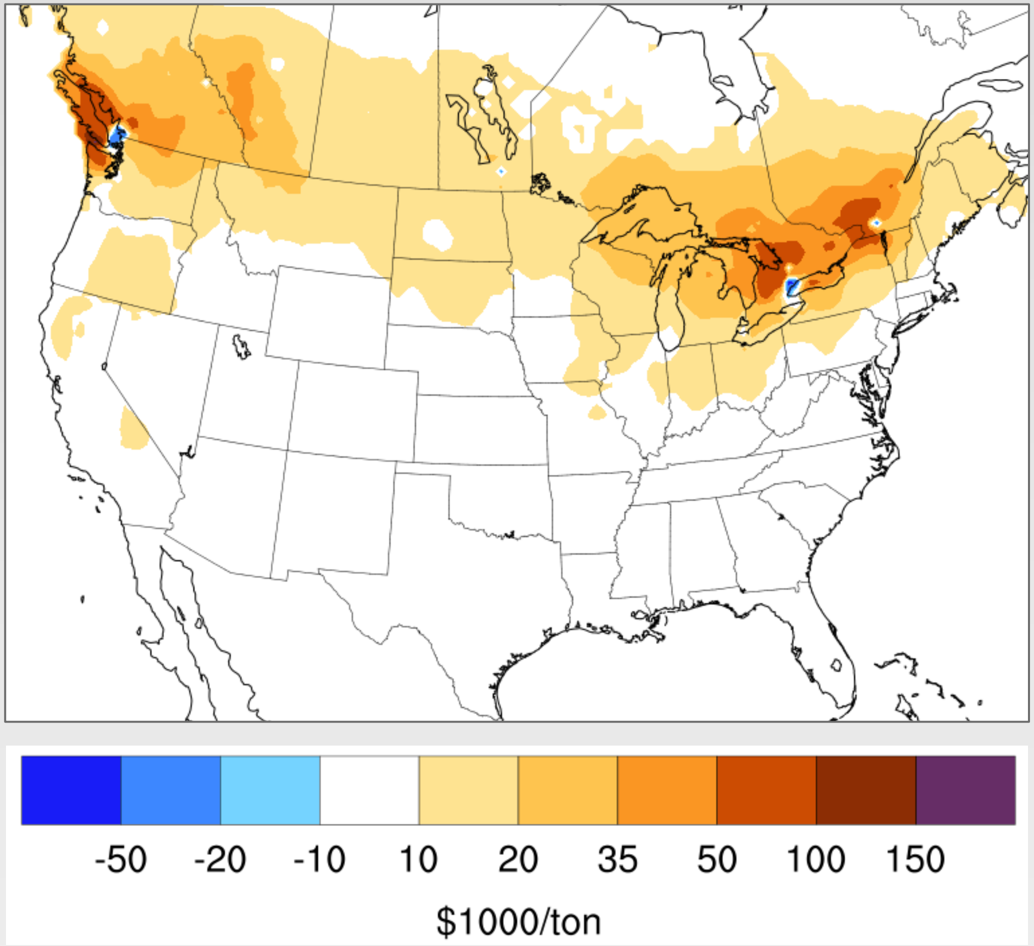
- O_3 $\beta = 0.0026\ ppb^{-1}$ (summertime average DM8A)
- NO_2 $\beta = 0.0059\ ppb^{-1}$ (summertime average)
- NO_2 log-linear $\beta = 0.0732$ (---note difficulty interpreting)

Findings: O_3 Mortality

- Linear CRF
- Non-linear atmospheric response

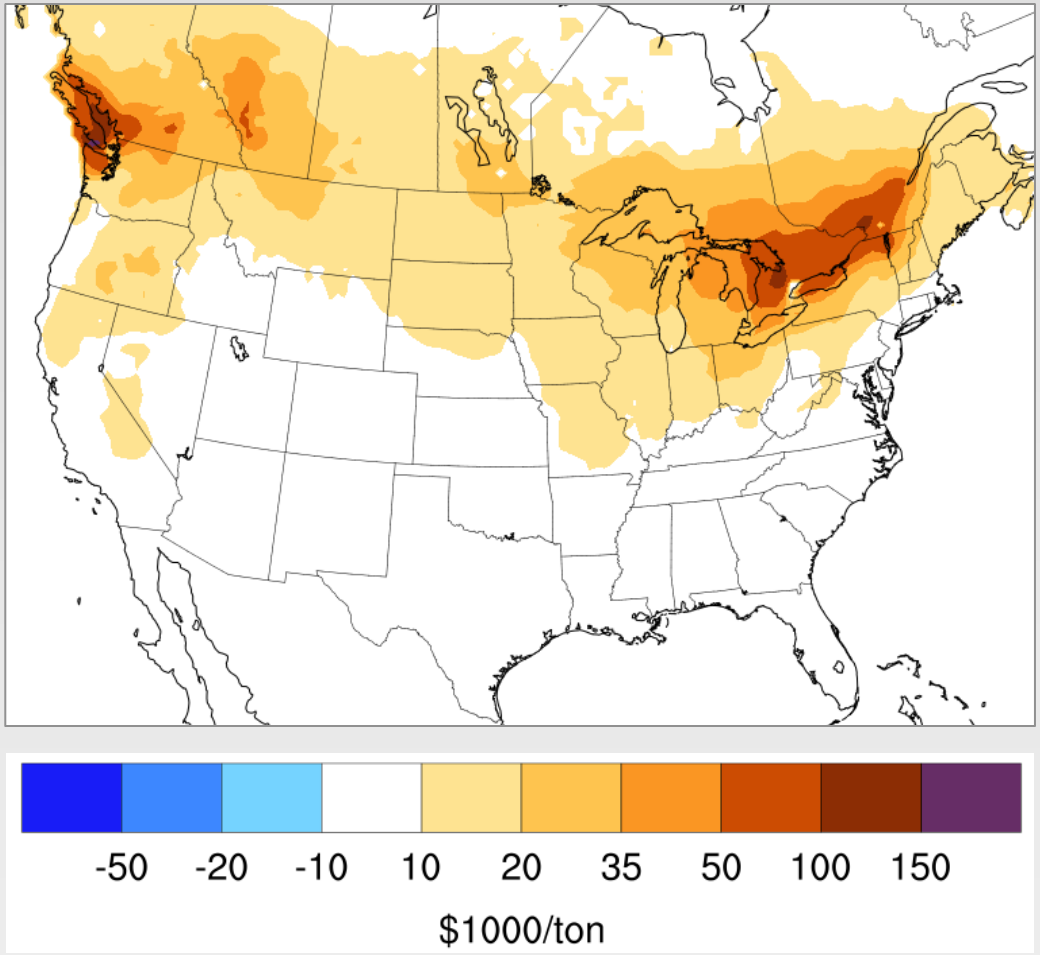
Benefits-per-ton of NO_x Control

O_3, At 2007 Emission Levels



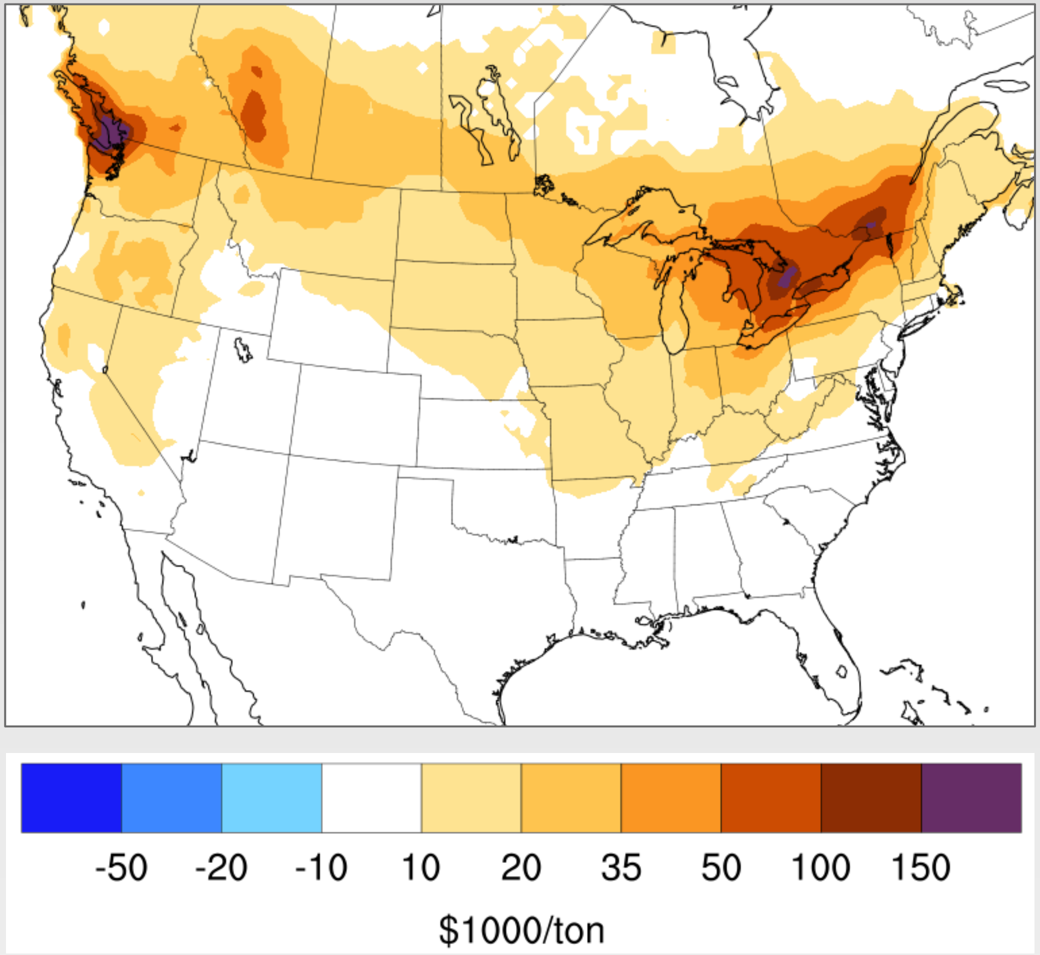
Benefits-per-ton of NO_x Control

O_3, At 50% Emissions Abatement

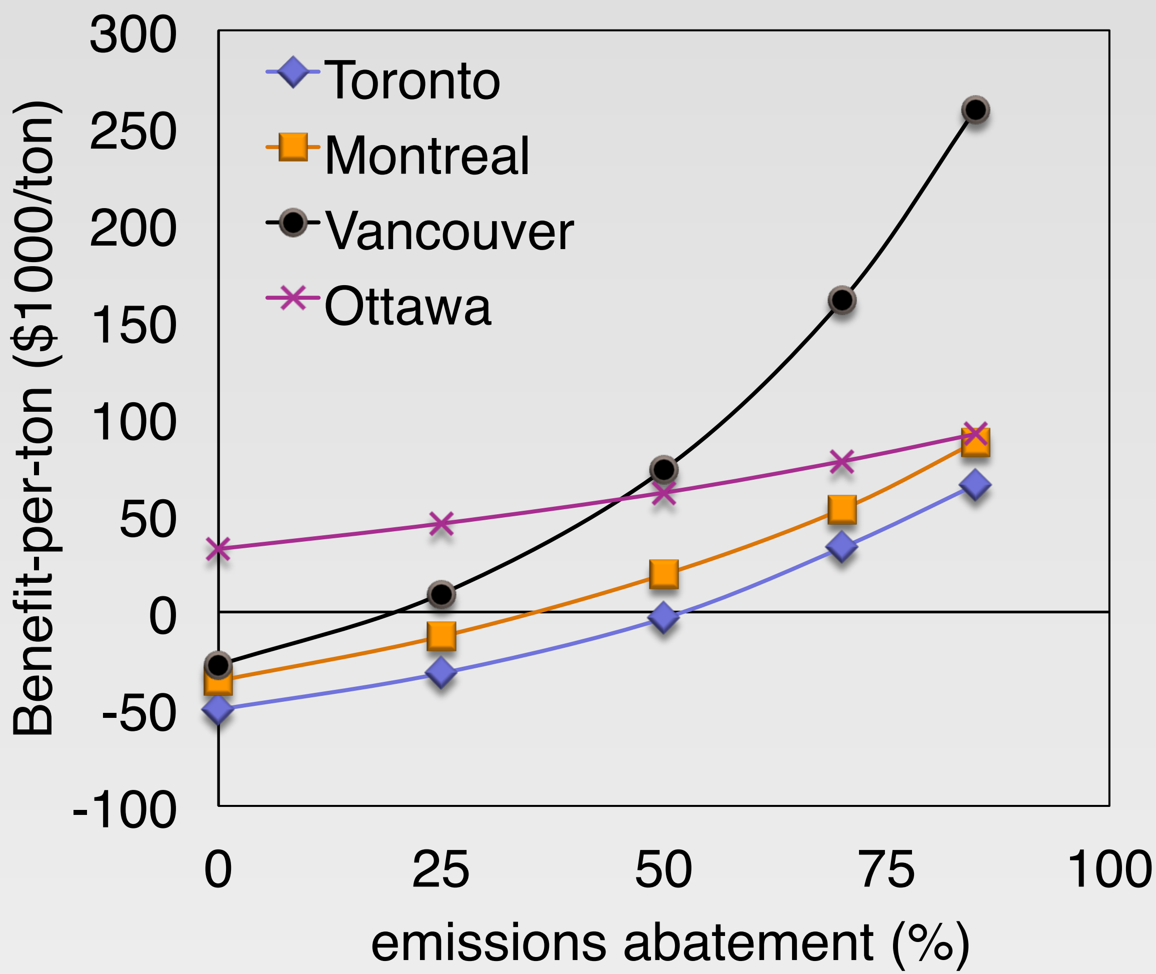


Benefits-per-ton of NO_x Control

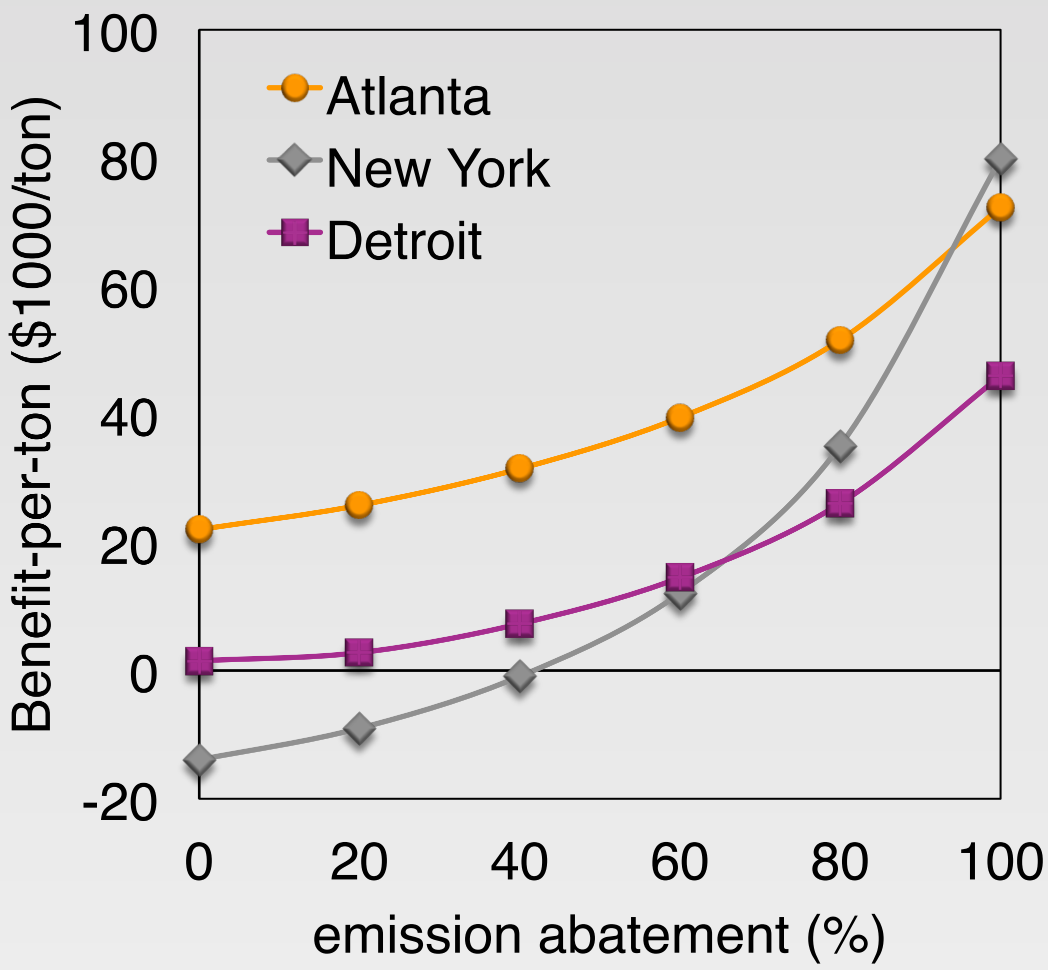
O_3, At 85% Emissions Abatement



Nonlinear Behavior by Source



Similar Behavior in the U.S.
(Pappin et al. ES&T 2015)



Conclusions - 1

- Non-linearity in O_3 based benefits are due entirely to atmospheric chemistry
- This becomes increasingly important as we move towards lower pollution levels

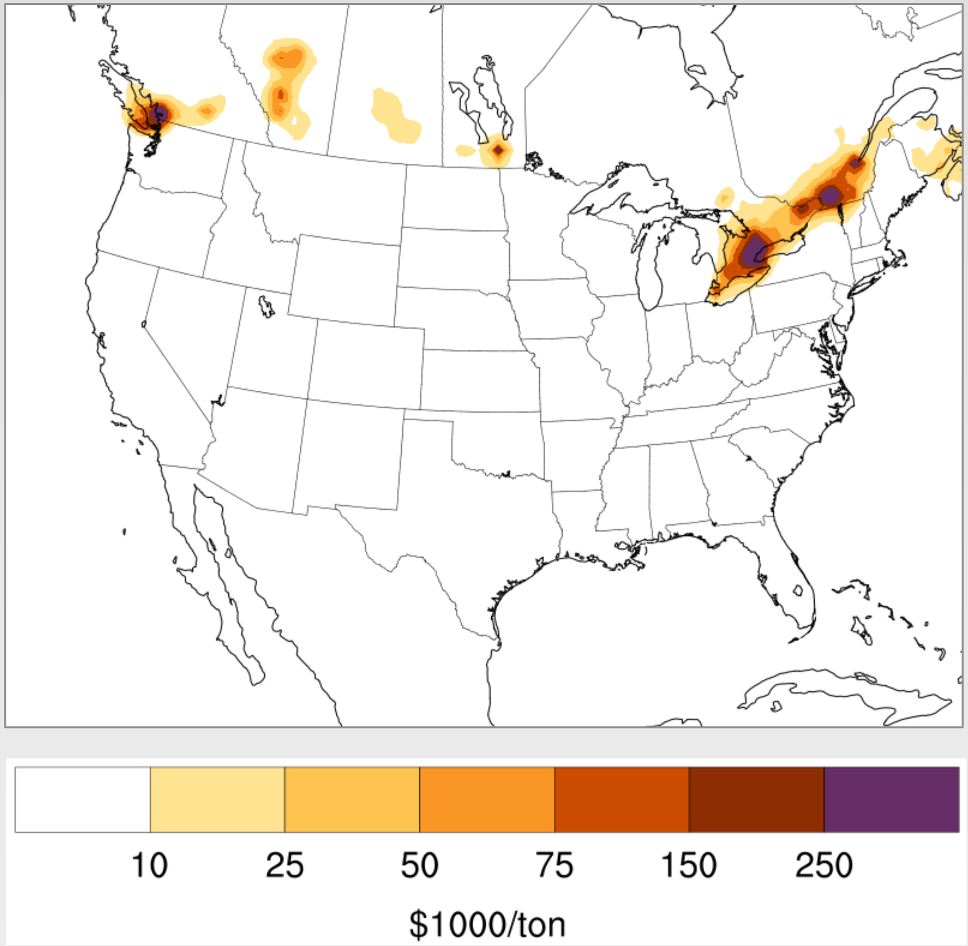
Findings: NO_2 Mortality

- Linear vs log-linear CRFs

Traditional, Linear CRF

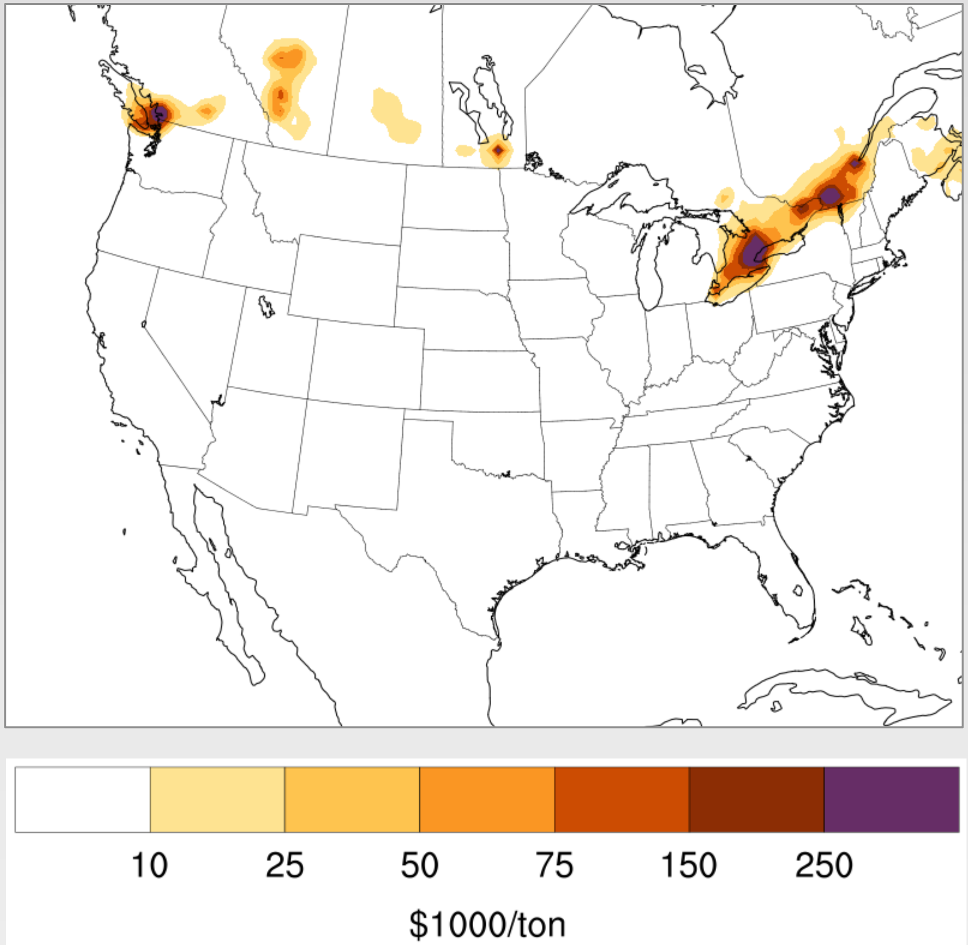
Benefits-per-ton of NO_x Control

NO_2, At 2007 Emission Levels



Benefits-per-ton of NO_x Control

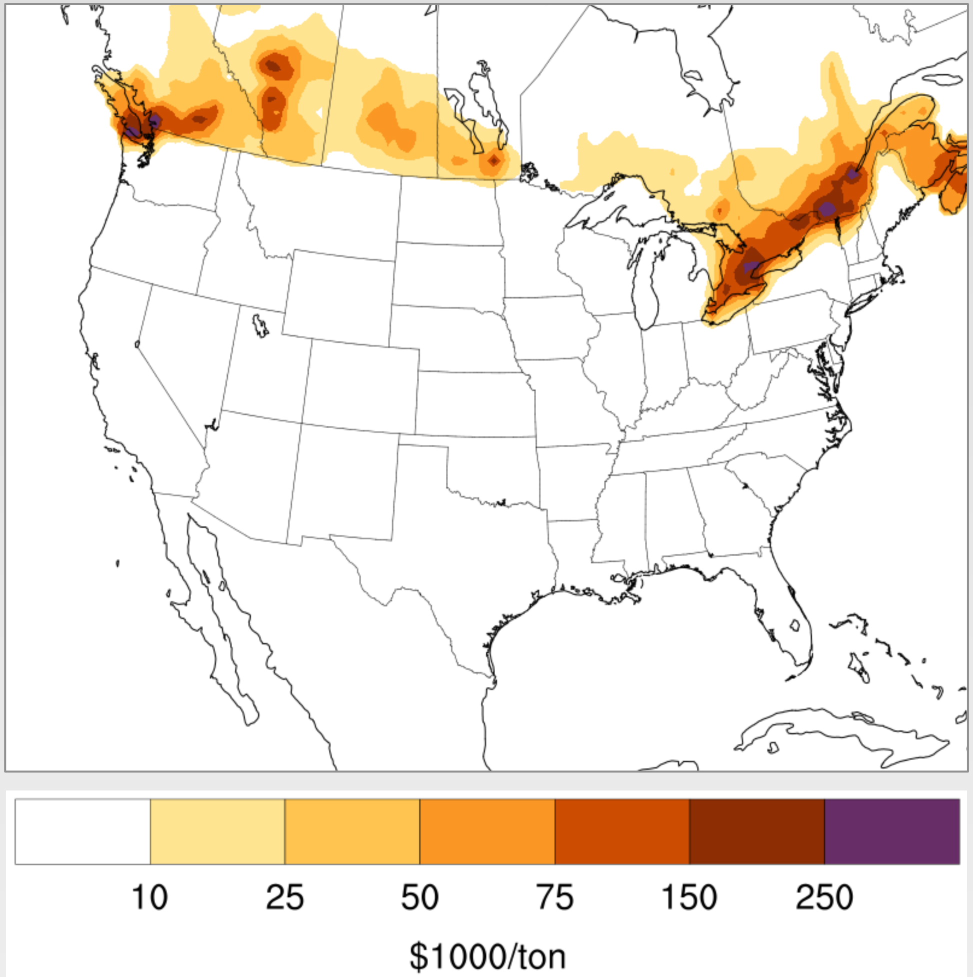
NO_2, At 85% Emissions Abatement

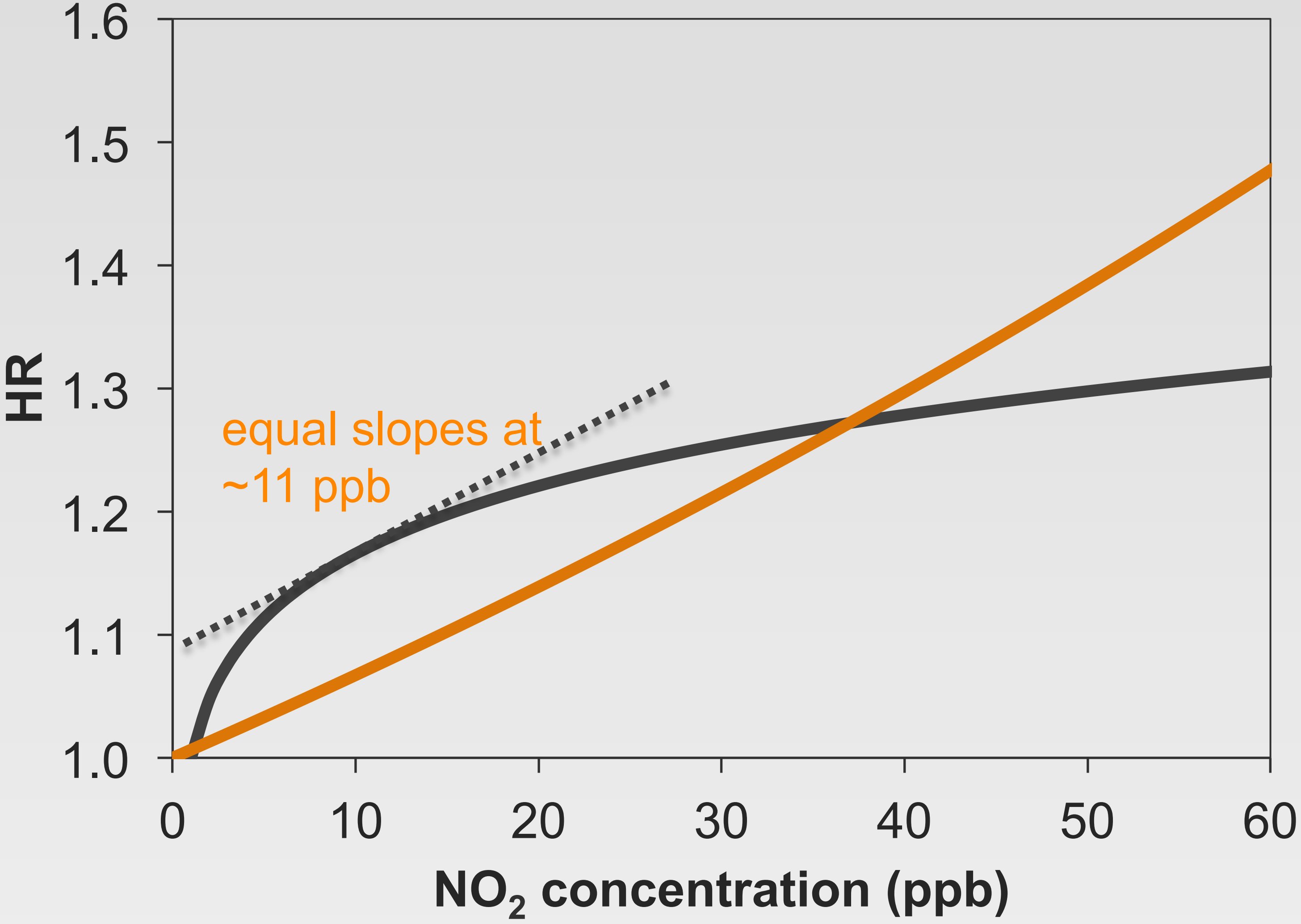


Log-linear CRF

Benefits-per-ton of NO_x Control

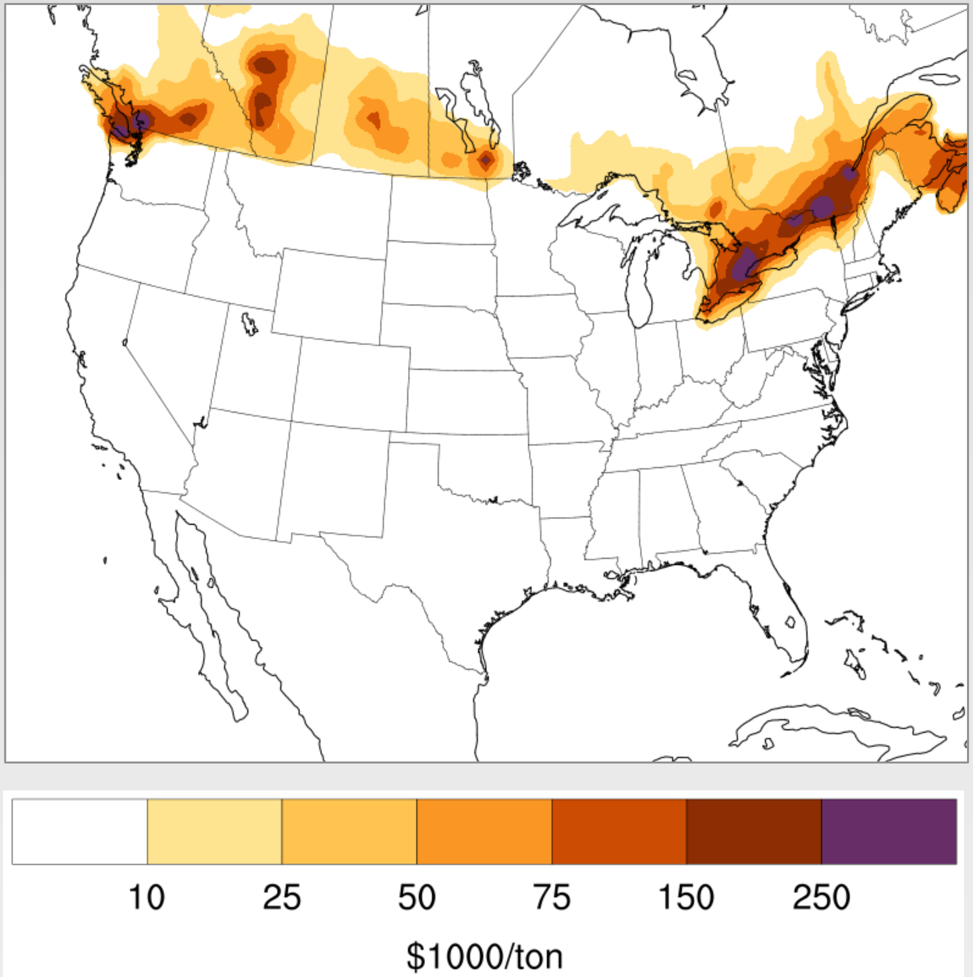
NO_2, At 2007 Emission Levels




1.6
1.5
1.4
1.3
1.2
1.1
1.0
HR
equal slopes at
~11 ppb
0
10
20
30
40
50
60
NO2 concentration (ppb)

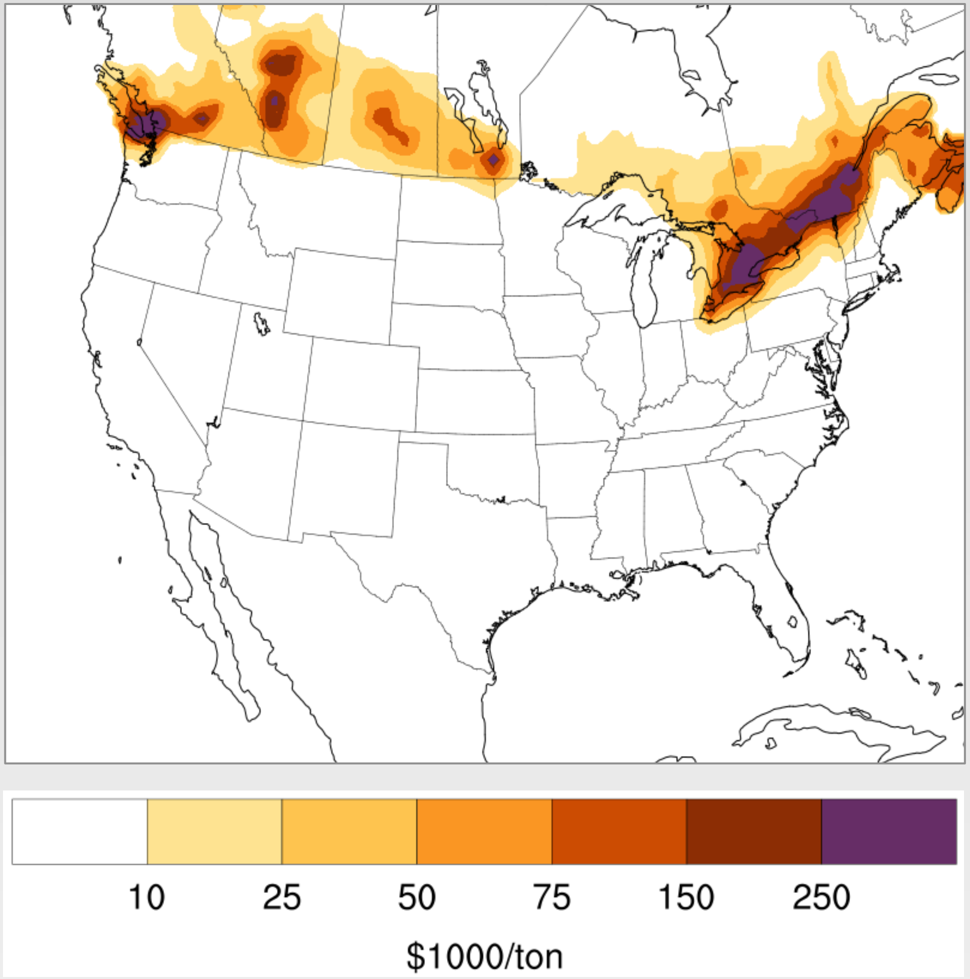
Benefits-per-ton of NO_x Control

NO_2, At 50% Emissions Abatement



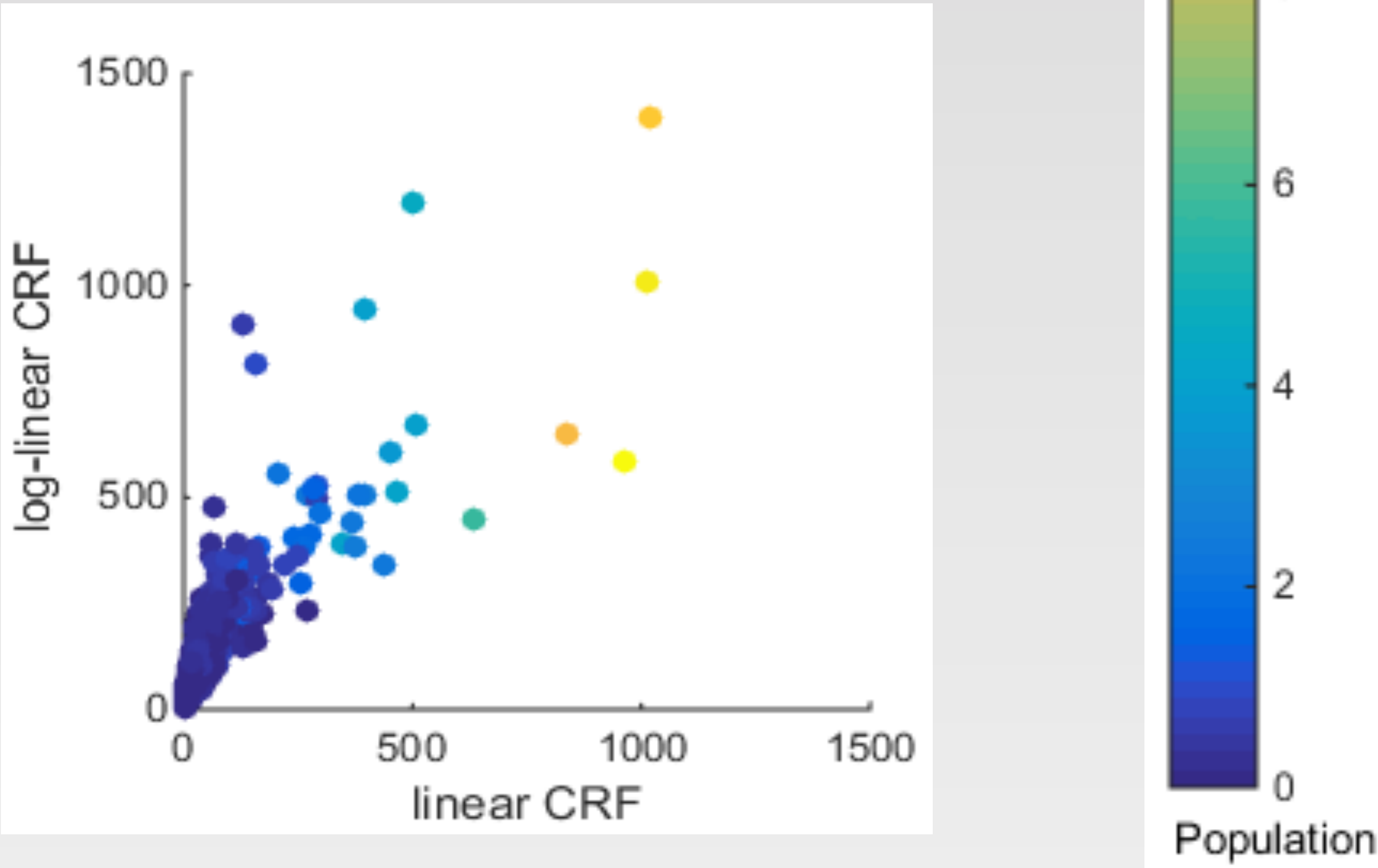
Benefits-per-ton of NO_x Control

NO_2, At 85% Emissions Abatement



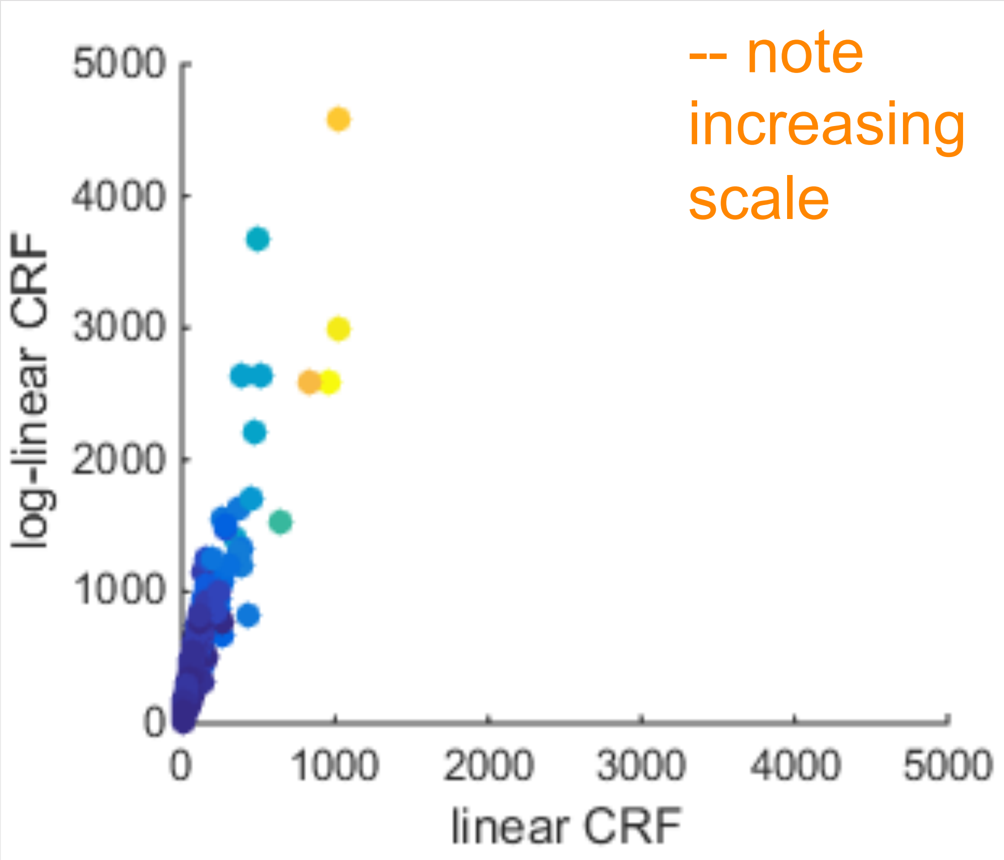
Linear vs Log-linear

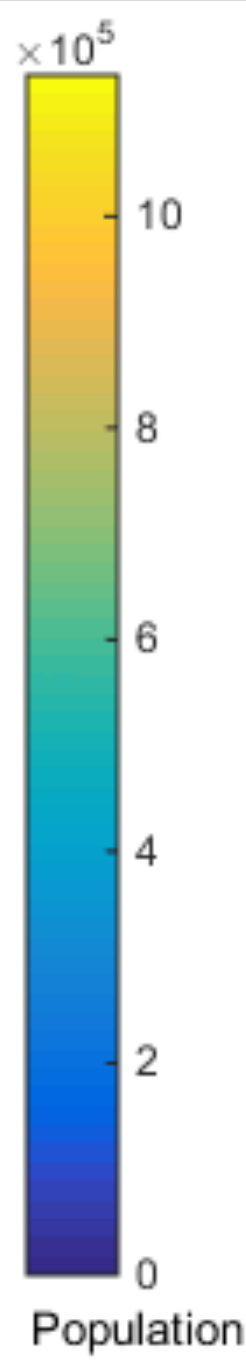
NO_2, At 2007 Emission Levels



Linear vs Log-linear

NO_2, At 85% Emissions Abatement

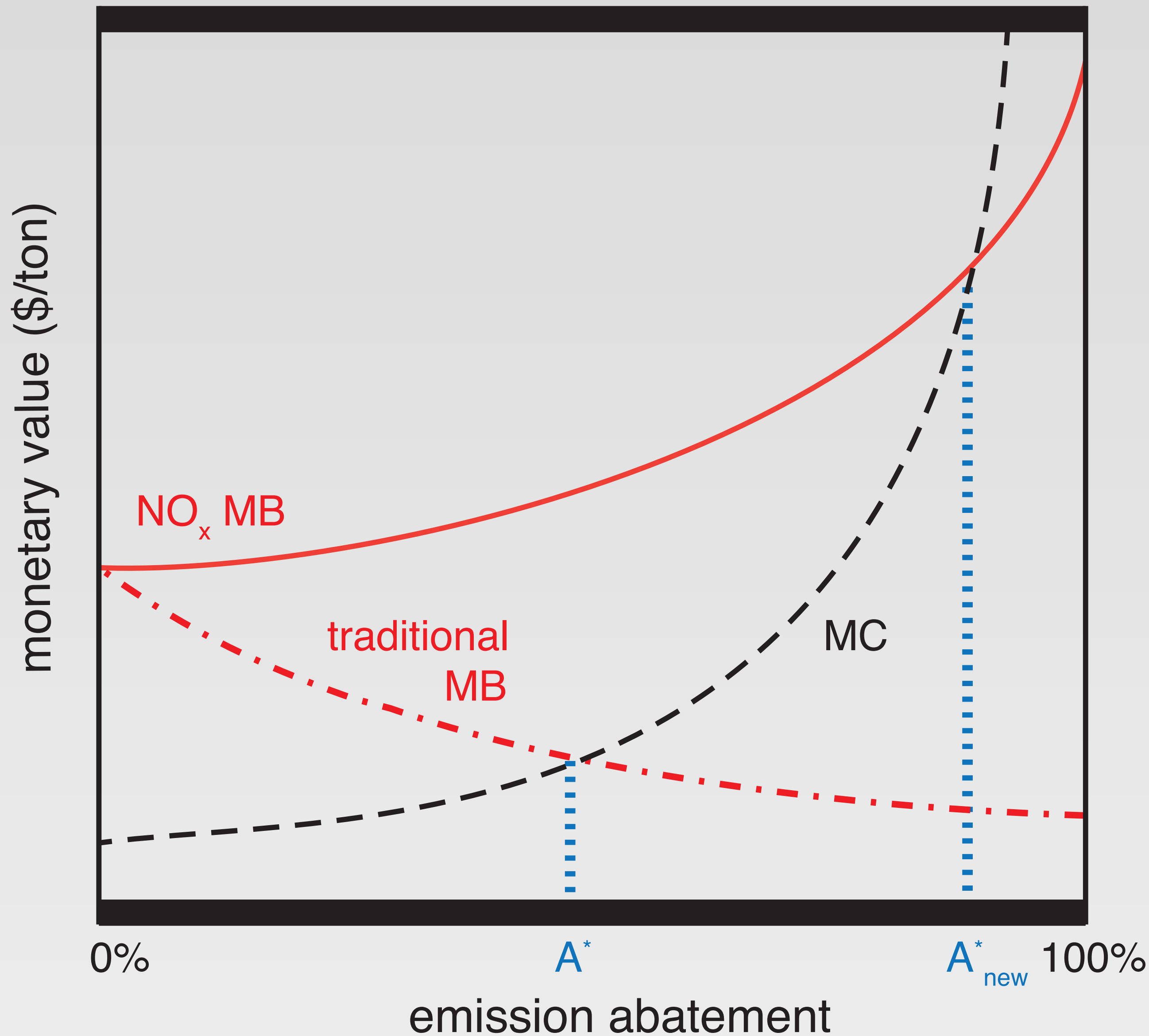




Conclusions - 2

- Important differences between linear and log-linear CRFs for NO_2, particularly in cleaner environments
- Benefits are larger for NO_2 than O_3

Policy Relevance



Pappin et al. ES&T 2015

Considerations for PM

- Indications of atmospheric nonlinearity for $PM_{2.5}$ exist in the literature (Fann et al. 2012; Holt et al. 2015; Hakami et al. 2003; Zhang et al. 2012)
- Combined with a potentially non-linear CRF, benefits-per-ton for $PM_{2.5}$ may increase substantially towards lower pollution levels
- Further research using a multiphase adjoint model can shed light on this

Acknowledgements

Stan Judek, Health Canada

This work was funded by Health Canada and NSERC.

Thank you!

Limitations

- Constant mortality rates assumed over time
- Long-term benefits (i.e., chronic exposure mortality) modeled in a short, 5-month simulation episode
- Uncertainty in atmospheric modeling, CRFs, and economic valuation lead to uncertainties in benefit-per-ton estimates

Canadian Census, Environment, and Health Cohort (CanCHEC)

- 2.6 million subjects > 25 years of age
- O_3, NO_2, $PM_{2.5}$ and mortality analyzed (various causes-of-death)
- Log-linear models appropriate for NO_2 and $PM_{2.5}$
- Linear model most appropriate for O_3

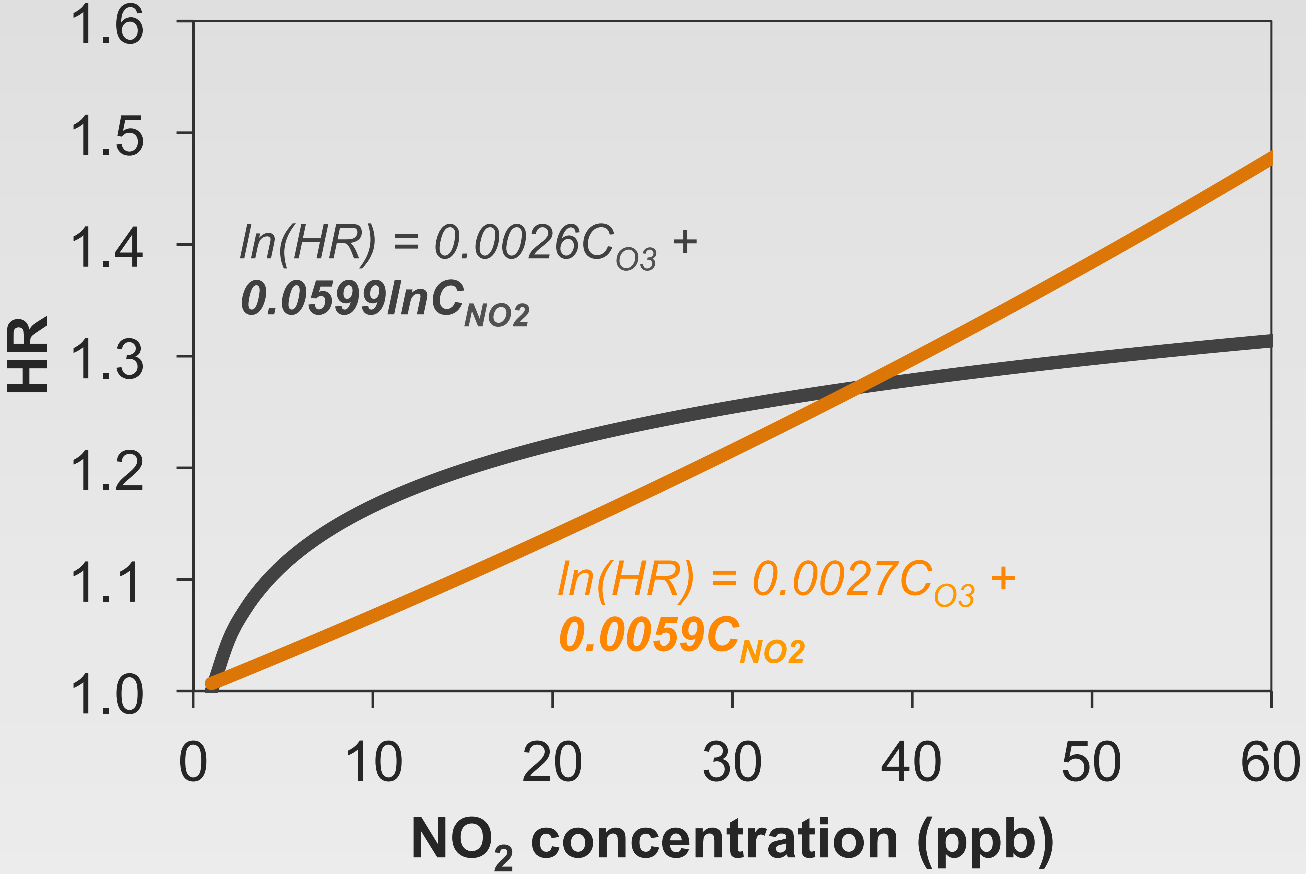
CanCHEC O_3 and NO_2 CRFs

Non-accidental mortality

- **Linear:** $ln(HR) = 0.0027C_{O3} + \underline{0.0059}C_{NO2}$ + *covariates*
- **Log-linear:** $ln(HR) = 0.0026C_{O3} + \underline{0.0599}\ln(C_{NO2}+1)$ + *covariates*

Linear and Log-linear NO_2 CRFs

Analysis of CanCHEC



Identifying Sources of Health Impacts

A question of sensitivity analysis

$$\frac{\Delta \text{Mortality}}{\Delta \text{Emissions}} = \underbrace{\frac{\Delta \text{Mortality}}{\Delta \text{Concentrations}}}_{\text{Epidemiology}} \times \underbrace{\frac{\Delta \text{Concentrations}}{\Delta \text{Emissions}}}_{\text{Air quality modeling}}$$