Ammonia emissions from livestock: a process-based modeling approach

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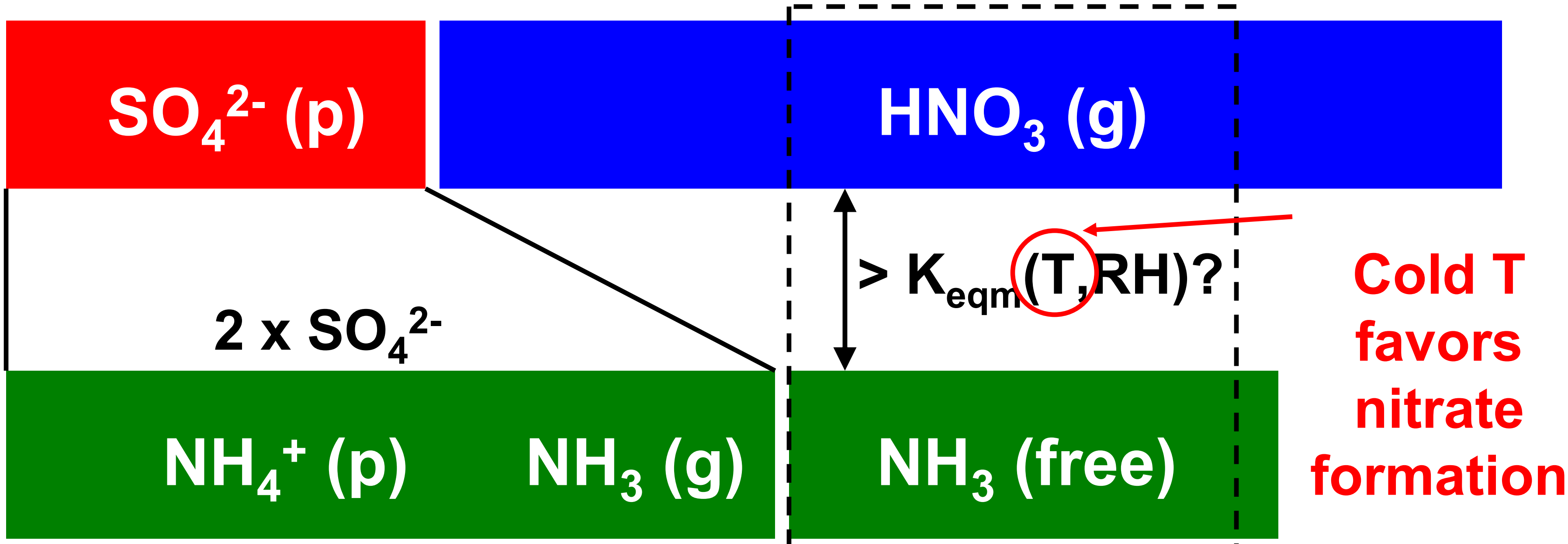
Carnegie Mellon
Civil and Environmental ENGINEERING

Inorganic $PM_{2.5}$ ($iPM_{2.5}$)

- Inorganic $PM_{2.5}$ ($iPM_{2.5}$) is typically half of $PM_{2.5}$
- Ammonia plays an important role in the formation of inorganic component ($iPM_{2.5}$):
  - **Sulfate (SO_4^{2-}):**
    - SO_2 (coal) → SO_4^{2-}
  - **Nitrate (NO_3^-):**
    - NO_x (combustion) → NO_3^-
  - **Ammonium (NH_4^+):**
    - NH_3 (agriculture) → NH_4^+
- Livestock is ~50% of national NH_3 emissions

SO_4-NO_3-NH_3 ($iPM_{2.5}$) Thermodynamics



Sulfate-N

Sulfate ae

Free amn

Nitrate ae

Net aeros

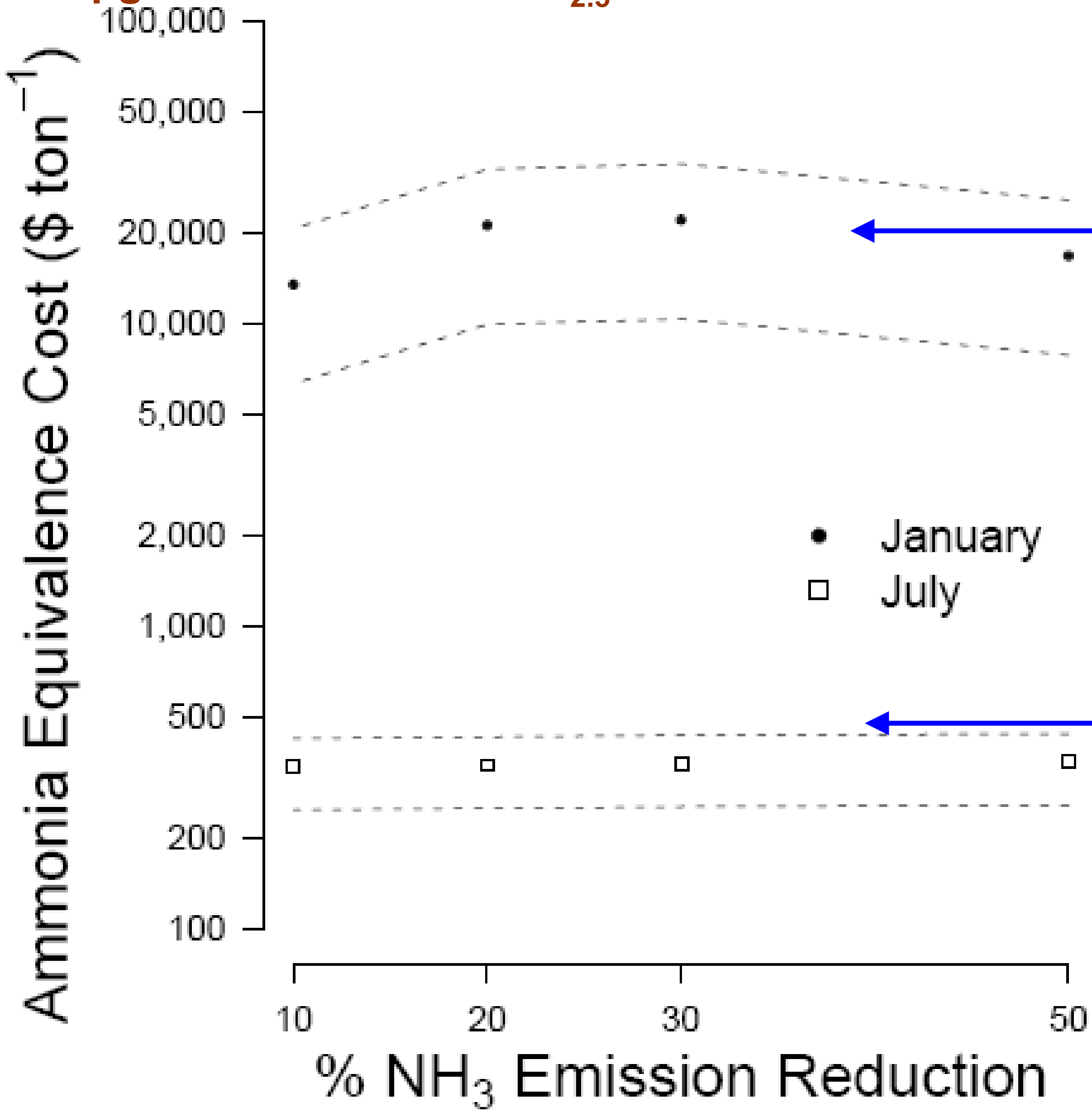
- **Ammonia is an "enabler" for nitrate PM formation**
- **$iPM_{2.5}$ highly sensitive to NH_3 *sometimes***
- **$iPM_{2.5}$ highly insensitive to SO_2/NO_x *sometimes***
- **Important to know seasonal and diurnal timing of emissions**

Are NH_3 Controls Cost-effective?

- **Ammonia Equivalence Cost (AEC)**:
  - Imagine $iPM_{2.5}$ mitigated by 1 ton NH_3 emissions reduction
  - Least-cost combination of SO_2 and NO_x controls that achieve same $iPM_{2.5}$ reduction
  - Should be willing to pay up to this amount for NH_3 reductions
- AEC is the cost of *avoided* SO_2 and NO_x controls due to NH_3 reductions

Ammonia Equivalence Cost

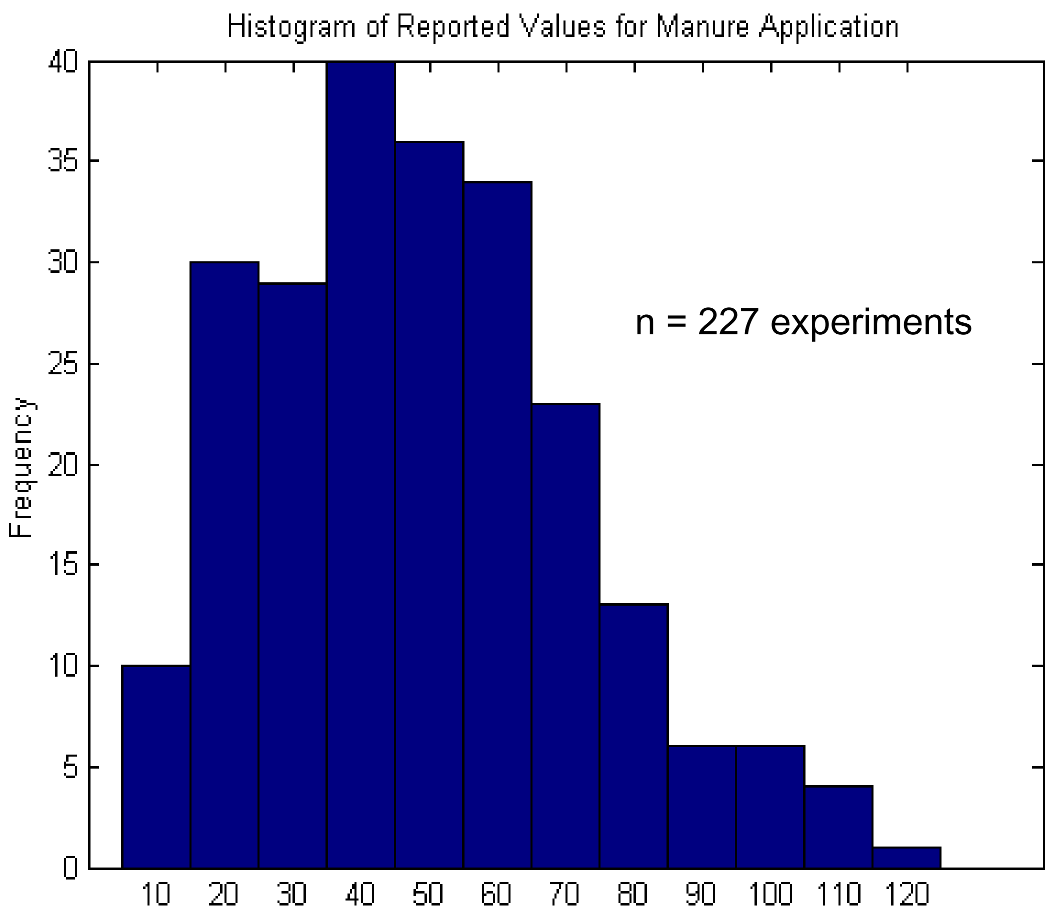
for 2 μg m^{-3} reduction in $iPM_{2.5}$



January: NH_3 controls up to $5,000 to $10,000 per ton are cost-effective

July: willingness to pay only $200-300 per ton reduced

Uncertainty and Variability



Manure Application: % Ammonia Volatilized

- Variability
  - Farming practices (housing, grazing, storage, application)
  - Weather conditions
- Uncertainty
  - Incomplete understanding
  - Measurement error

Source: Plochl, Matthias. Neural network approach for modelling ammonia emission after manure application on the field, *Atmospheric Environment*. 35 (2001) 5833-5841

Process-Based Models

- Emission rate = (Emission factor) x (Activity level)
- Standard approach
  - Pick an average emission factor from literature
  - Loses some variability information
- Process-based modeling approach
  - Simulate mass balance of farm nitrogen and its volatilization as NH_3
  - Inputs: farming practices, meteorology
  - Outputs: NH_3 emissions as a function of time
  - Predict variability in emissions
  - Evaluate/tune for consistency with measured emissions factors
  - Analyze potential emissions reductions
  - Self-consistency of mass balance approach

New Data Sources

- National Air Emission Monitoring Study (NAEMS)
  - >20 dairy, pork, poultry facilities
  - 9 states
  - 2 years of emissions monitoring
  - Emissions from housing, manure storage, spreading
- Ambient total ammonia (NH_x) data
  - Traditional networks measure deposition or NH_4^+ (aerosol) concentrations
  - Total ammonia $NH_x = NH_3 + NH_4^+$ is better indicator
  - NADP Ammonia Monitoring Network (AMoN)

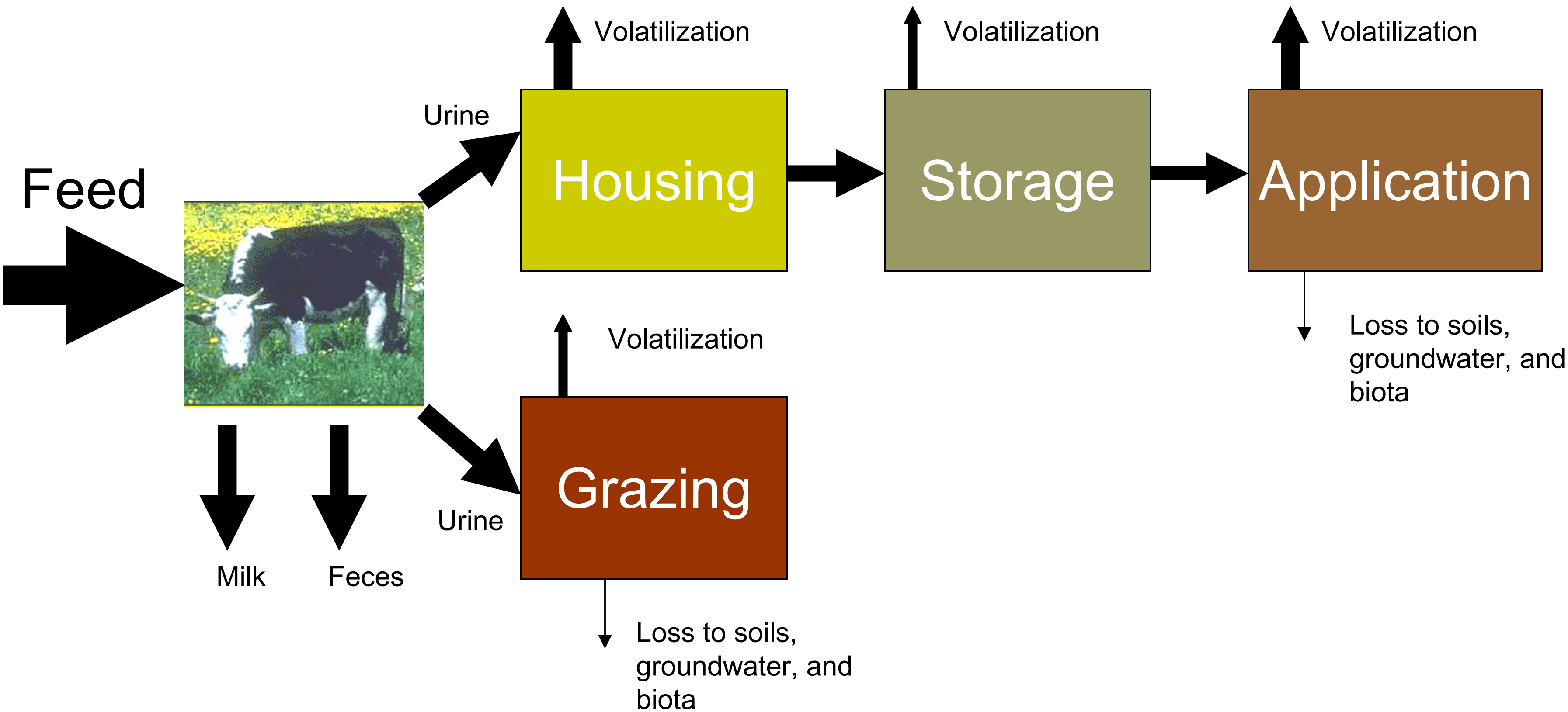
Research Objectives

- Develop process-based models for beef cattle, swine, and chickens
- Assess the uncertainty in livestock ammonia emissions, suggest sources of data that can help
- Test process-based models at the farm scale against NAEMS multi-year measurements
- Develop a revised national emissions inventory based on these results
- Test the performance of the revised emissions inventory in a CTM against ambient measurements, especially NH_x data
- Assess the sensitivity of inorganic $PM_{2.5}$ to NH_3, SO_2, and NO_x emissions under current and future policy regimes

Research Tasks

- **Task 1**: Development of Farm Emissions Models (FEMs) for major livestock types
- **Task 2**: Evaluation of farm modules versus NAEMS
- **Task 3**: Development of National Practice Models (NPMs) for major livestock types
- **Task 4**: Updates to the CMU Ammonia Inventory
- **Task 5**: CTM Modeling: Inventory Evaluation and $PM_{2.5}$ Sensitivity

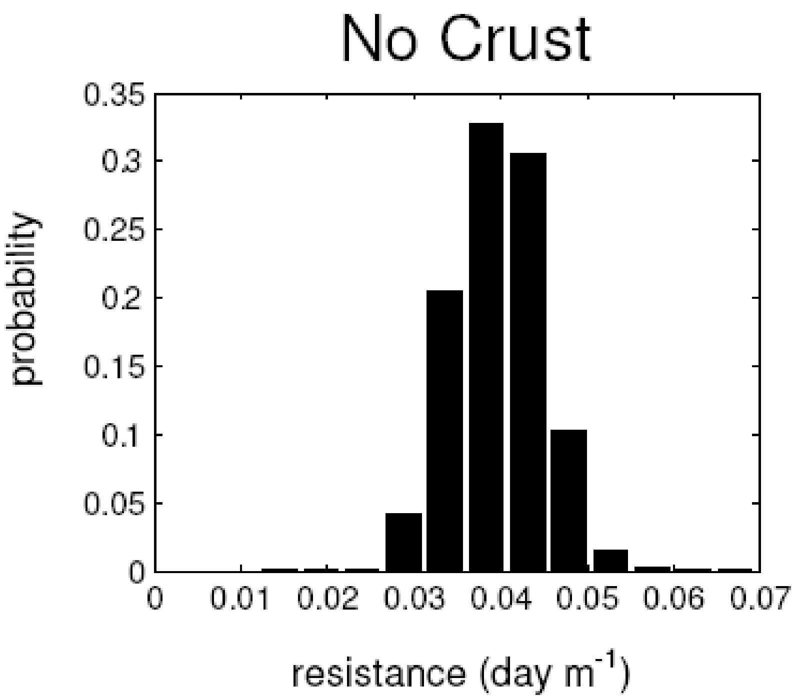
Farm Emissions Model: Nitrogen Flows

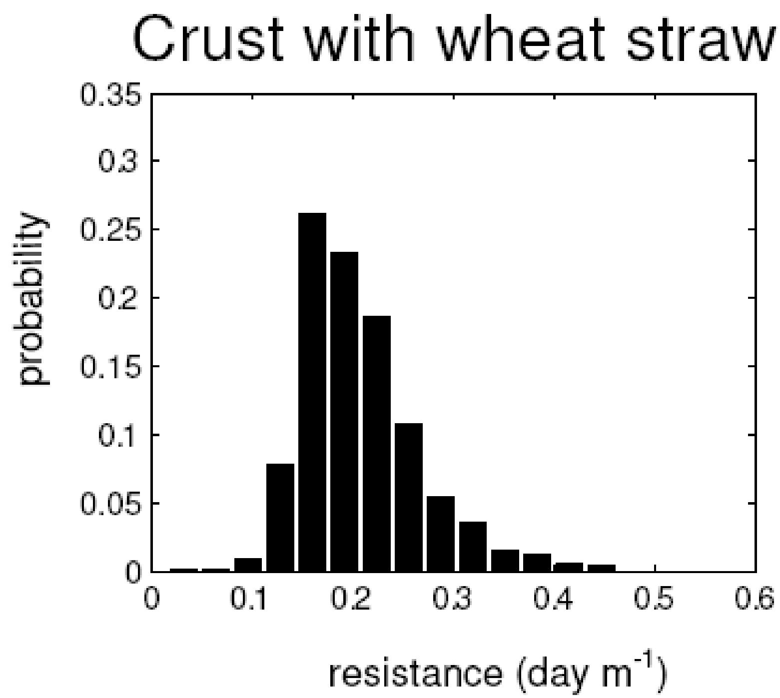


- **Inputs:** meteorology, manure characteristics, and farming practices
- **Model:** flow of nitrogen, water, manure volume through animal operation
- **Outputs**: NH_3 emissions via volatilization
- **Governing Equation**:

$$E = A\,[NH_x]\,H^*\,r^{-1}$$

Estimated Probability Distribution for Model Input Parameters

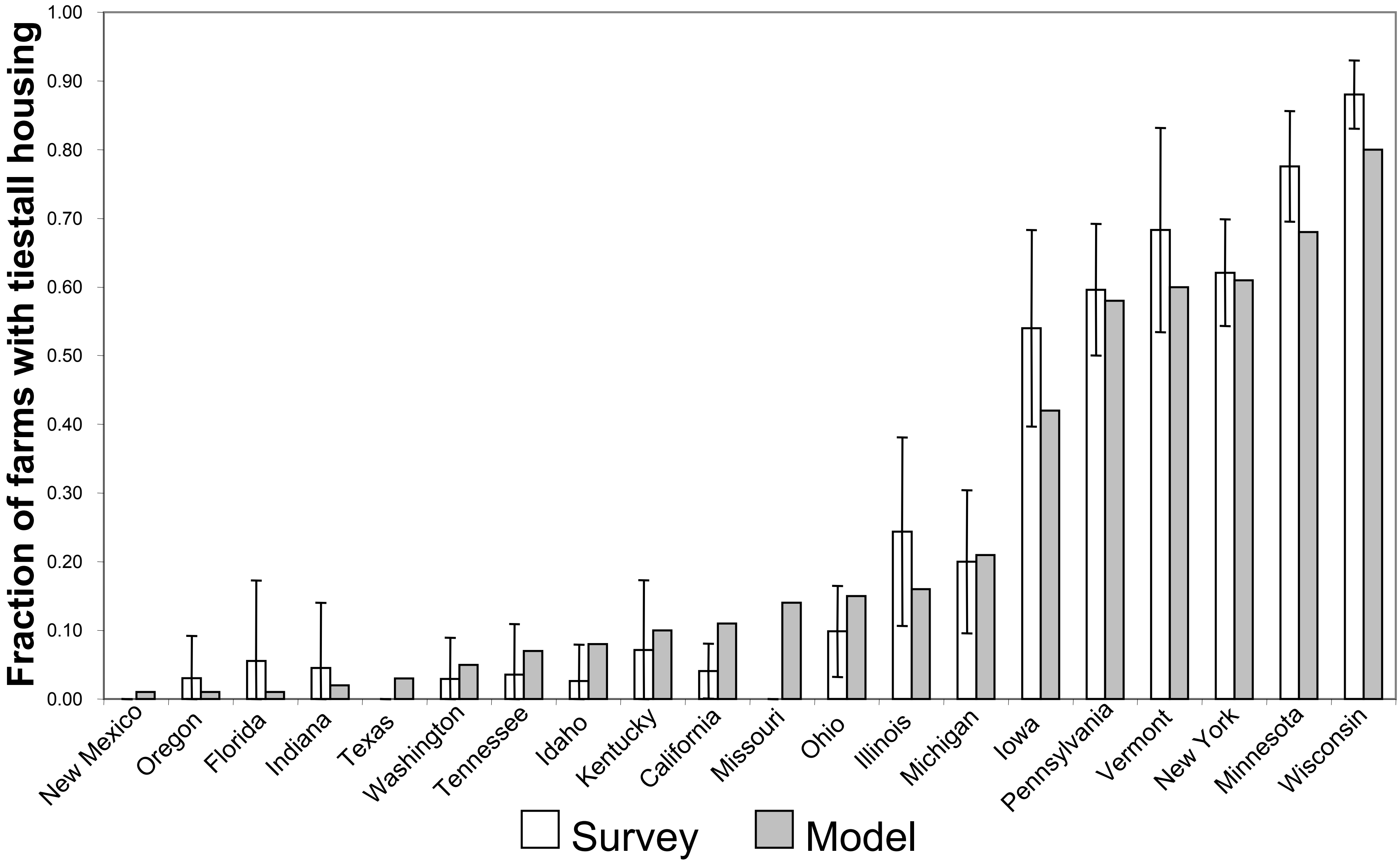


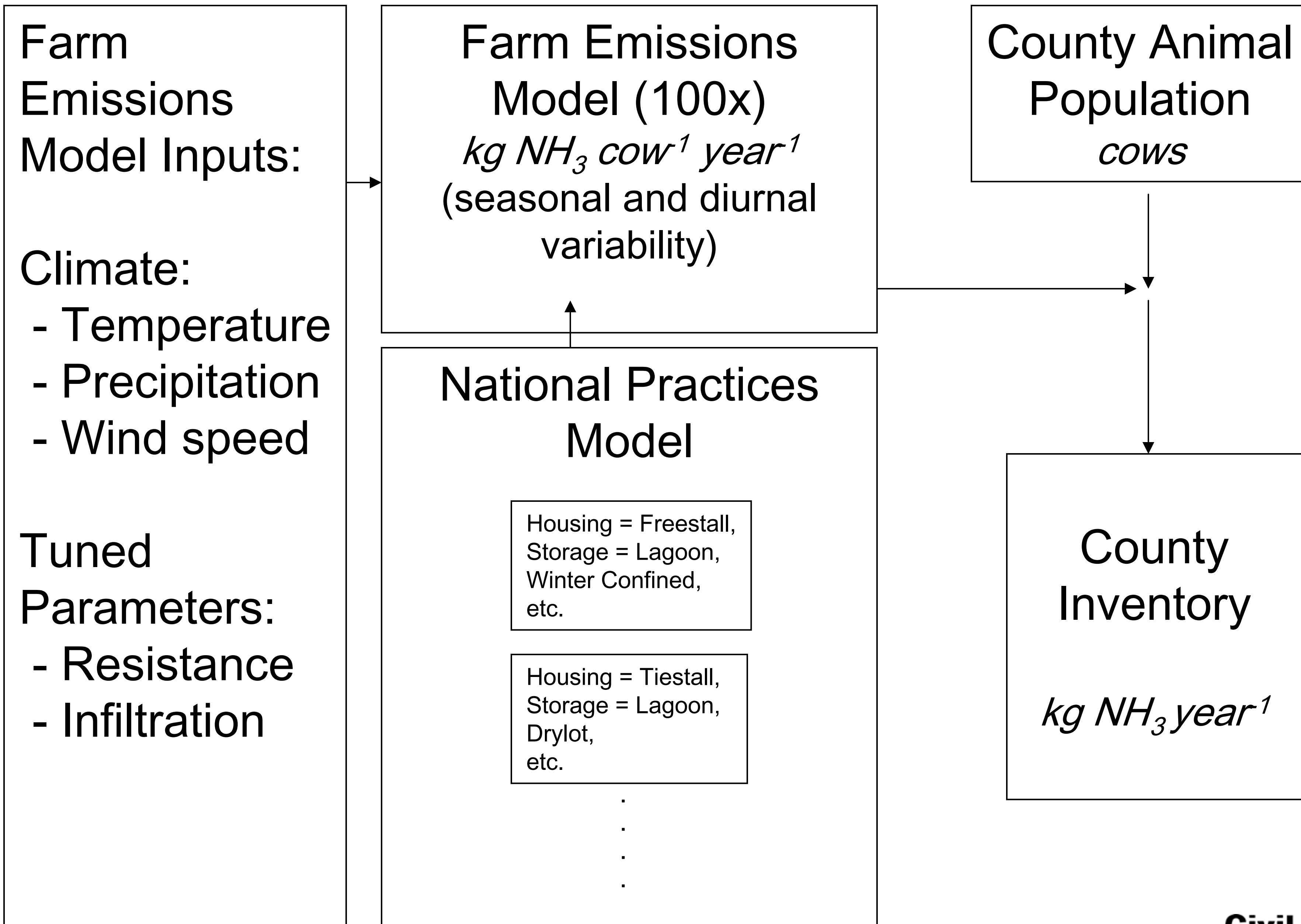


•Different resistances capture differences in farming practices

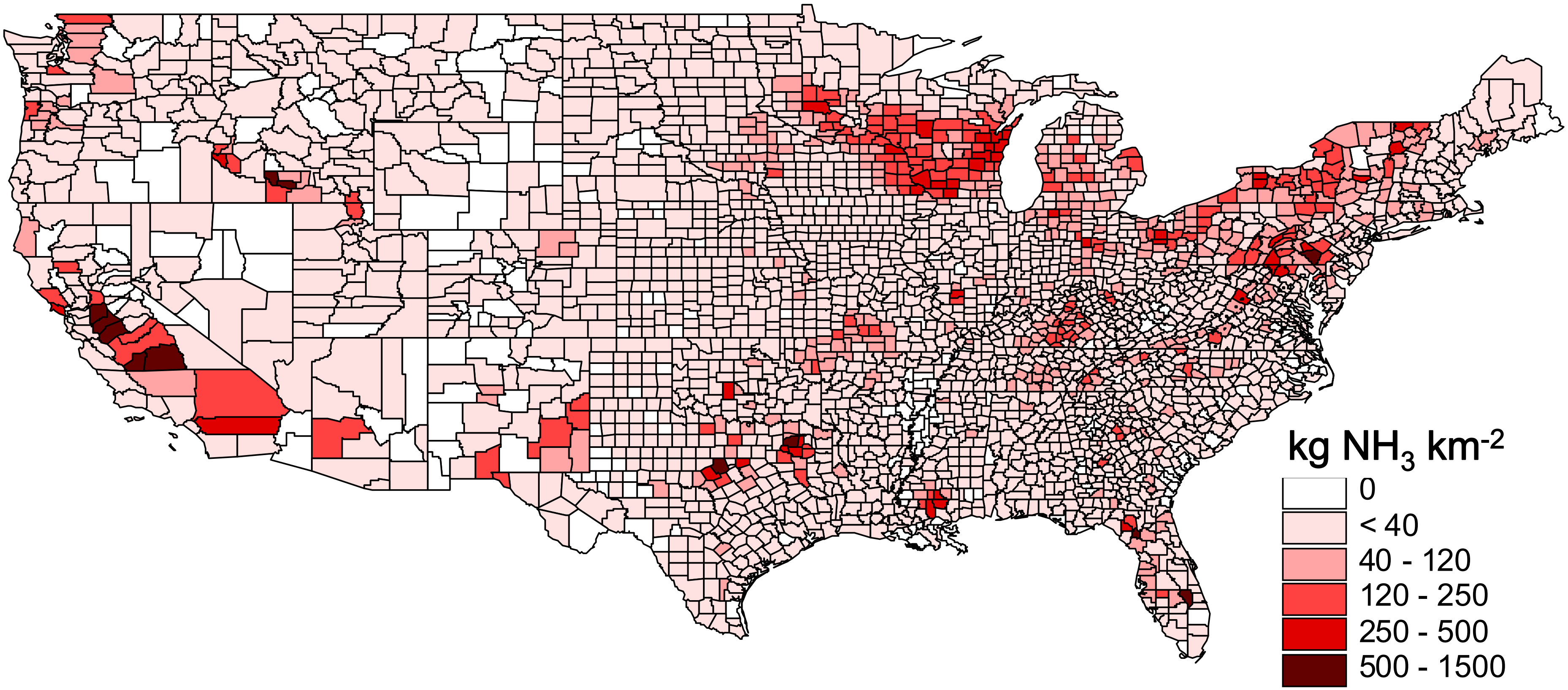
•Probability distributions allow for uncertainty analysis

National Practice Models




Farm Emissions Model Inputs:
Climate:
- Temperature
- Precipitation
- Wind speed
Tuned Parameters:
- Resistance
- Infiltration
Farm Emissions Model (100x)
kg NH_3 cow^{-1} $year^{-1}$
(seasonal and diurnal variability)
National Practices Model
Housing = Freestall, Storage = Lagoon, Winter Confined, etc.
Housing = Tiestall, Storage = Lagoon, Drylot, etc.
County Animal Population
cows
County Inventory
kg NH_3 $year^{-1}$

National Inventory



- **CMU Inventory (http://www.cmu.edu/ammonia/)**
- **Downloaded ~300 times (2-3 times per week)**

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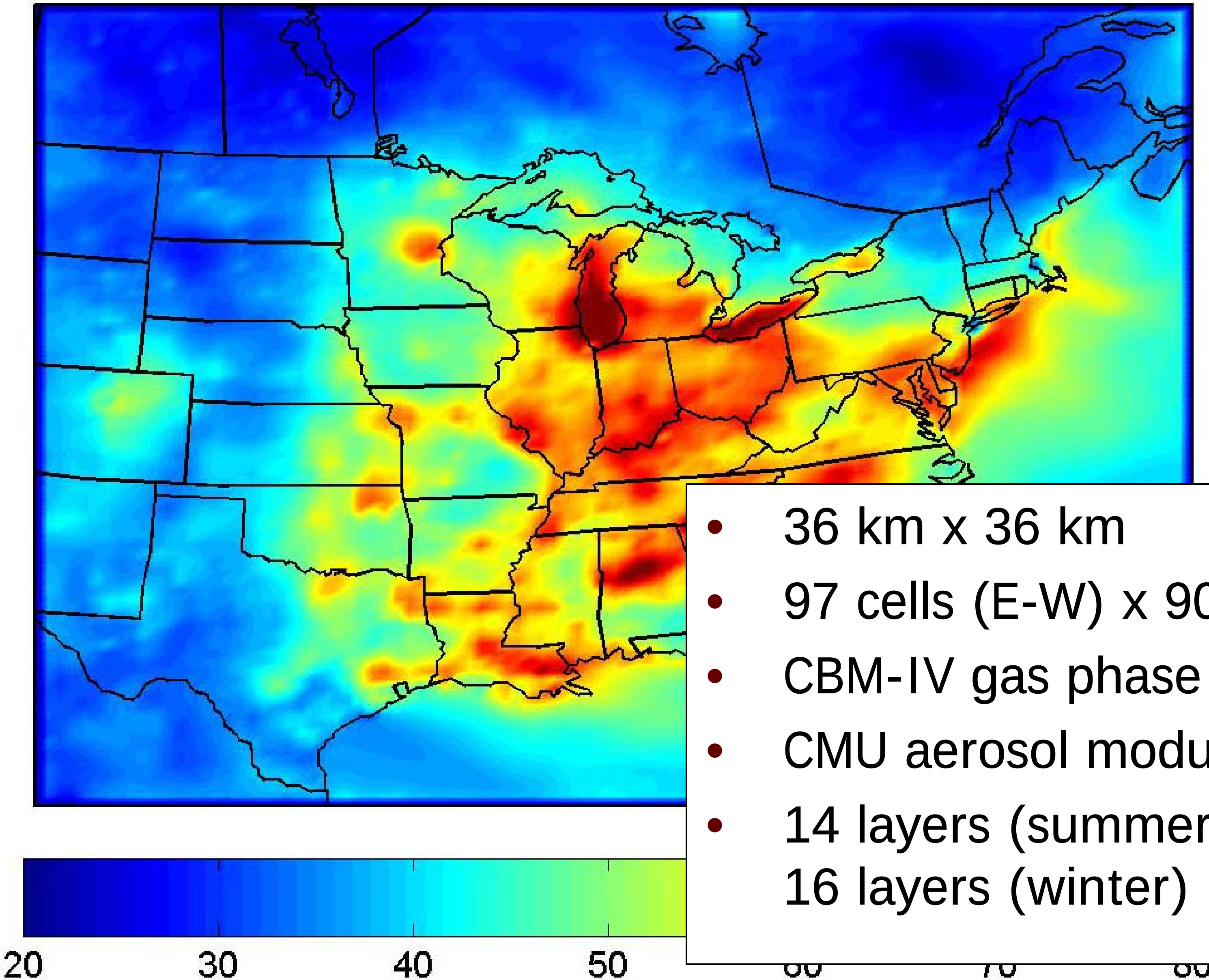
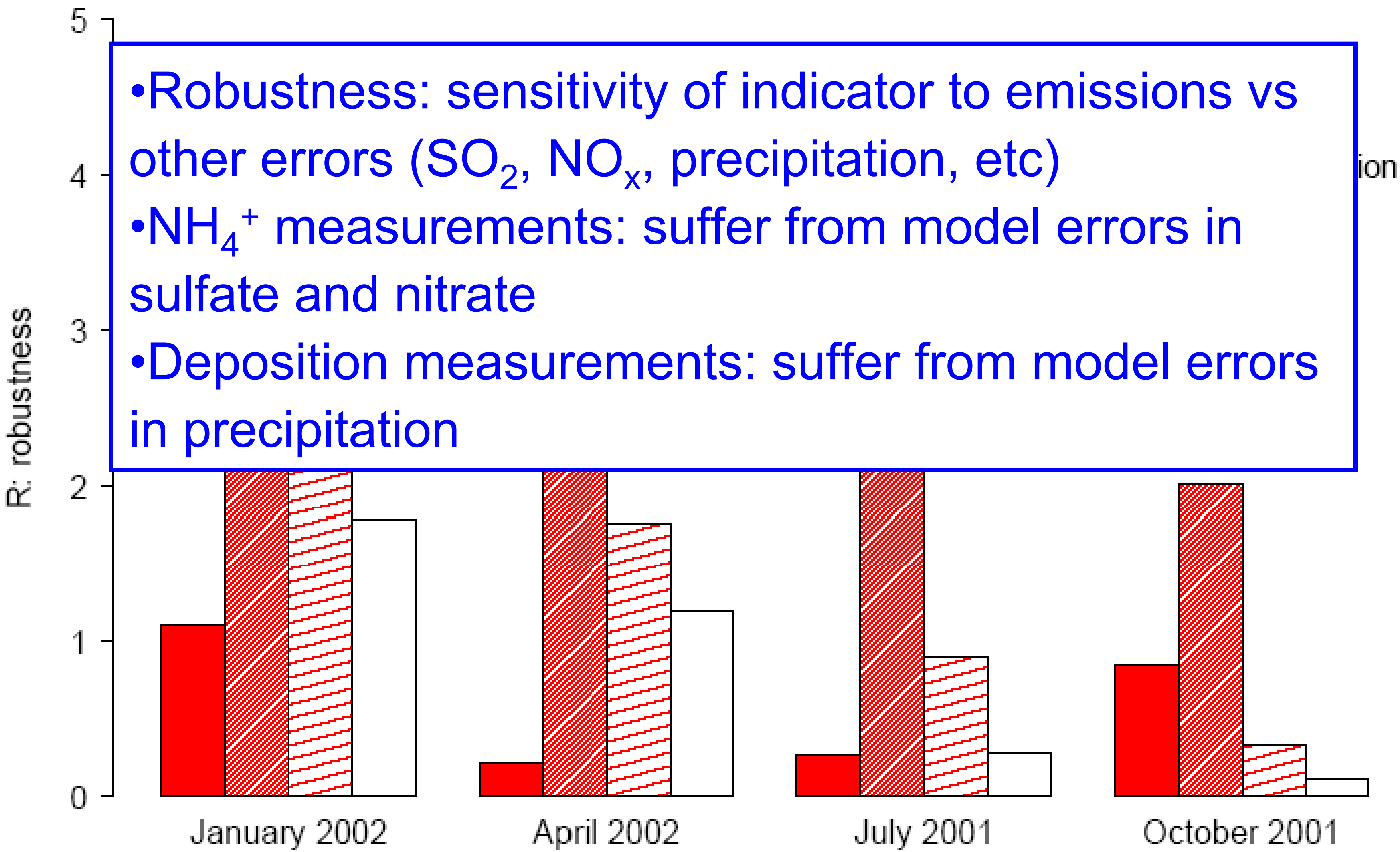
PMCAMx Chemical Transport Model



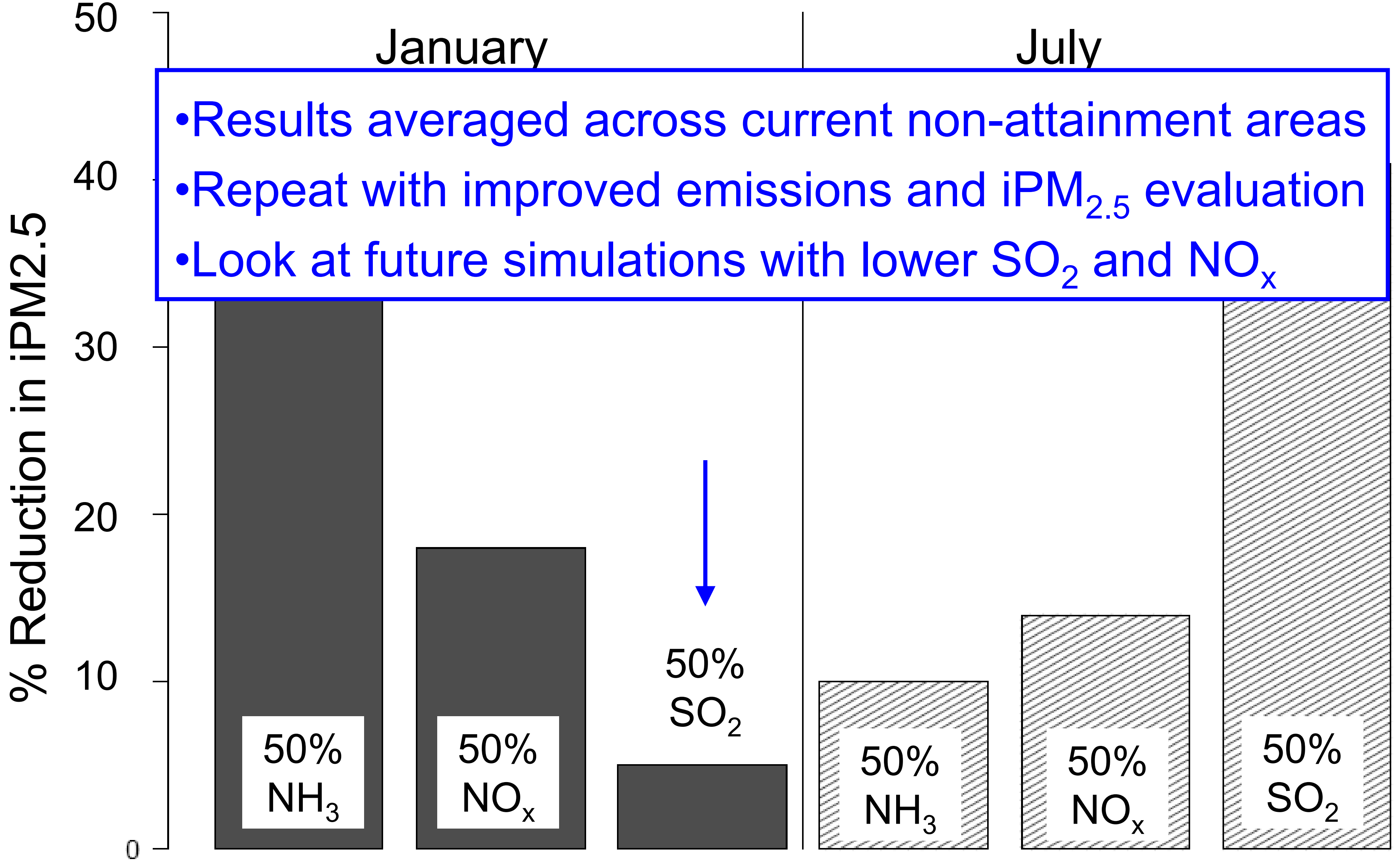
- 36 km x 36 km
- 97 cells (E-W) x 90 cells (N-S)
- CBM-IV gas phase chemistry
- CMU aerosol modules
- 14 layers (summer)
  16 layers (winter)

NH_x is Most Robust Indicator for NH_3 Emissions



- Robustness: sensitivity of indicator to emissions vs other errors (SO_2, NO_x, precipitation, etc)
- NH_4^+ measurements: suffer from model errors in sulfate and nitrate
- Deposition measurements: suffer from model errors in precipitation

Effectiveness: $iPM_{2.5}$ Sensitivity



- Results averaged across current non-attainment areas
- Repeat with improved emissions and $iPM_{2.5}$ evaluation
- Look at future simulations with lower SO_2 and NO_x

Outputs and Impacts

- Complete process-based modeling tool for ammonia from all livestock types
- Better knowledge of seasonal, diurnal, and regional distribution of NH_3 emissions
- Evaluation of sensitivity of $PM_{2.5}$ to NH_3 as function of location and season
- Tool for mitigation analyses