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Health Damages from Dairy Air Pollution: Evidence from New Mexico

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This study quantifies health damages from dairy CAFO air emissions in New Mexico using farm-level atmospheric dispersion modeling, epidemiological concentration-response functions, and economic valuation. We estimate 20.6 annual premature deaths and \$217.66 million in health costs (90% CI: \$146.8–\$297.6 million), equivalent to 15% of state dairy revenues. Over 99% of damages arise from unregulated ammonia emissions forming secondary $PM_{2.5}$. Per-cow damages range from \$544 (rural) to \$1,086 (metro), driven by receptor population density rather than farm size. Extrapolation to major dairy states suggests national damages of \$10.1–\$64.9 billion annually, with a preferred estimate of \$33.4 billion.

Key words: ammonia emissions, atmospheric dispersions, benefit-cost analysis, CAFOs, externalities, InMAP, value of a statistical life

Introduction

Agricultural production generates significant unpriced externalities, yet livestock operations remain among the least regulated sources of air pollution in the United States (US). Concentrated Animal Feeding Operations (CAFOs) emit large quantities of ammonia (NH_3) and fine particulate matter ($PM_{2.5}$), imposing health costs that are not internalized by producers or reflected in the prices of agricultural commodities. This market failure constitutes a classic case for externality pricing and corrective policy intervention (Muller and Mendelsohn, 2009). Despite the well-established framework for benefit-cost analysis in environmental regulation, empirical estimates of the damages attributable to livestock air pollution remain limited, particularly at the farm level.

A growing body of agricultural economics literature documents the external costs of livestock production, including water quality degradation (Ribaudo et al., 2003), antibiotic resistance (Gilchrist et al., 2007), and greenhouse gas emissions (MacDonald, Hoppe, and Newton, 2018). Air pollution from CAFOs has received less systematic treatment, despite evidence that NH_3 is a primary driver of secondary $PM_{2.5}$ formation (Paulot et al., 2014). Existing studies rely on density- or proximity-based exposure metrics (Sneeringer, 2009) that do not support the dose-response estimation needed for benefit-cost assessment. Domingo et al. (2021) estimate \$36 billion annually in health costs from all US agricultural NH_3 but rely on national aggregates that obscure the farm-level heterogeneity. Our approach extends the spatially disaggregated damage function of Muller and Mendelsohn (2007; 2009) and Goodkind et al. (2019), to estimate farm-level marginal damages, addressing a core gap in the nonpoint-source externality literature (Shortle and Horan, 2001).

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This study makes three contributions. First, we provide farm-level estimates from dairy CAFOs using the Intervention Model for Air Pollution (InMAP; Tessum et al., 2017), a spatially resolved atmospheric model that tracks NH_3 and $PM_{2.5}$ from source to receptor across the contiguous US Second, we combine these dispersion estimates with the concentration-response function (CRF) from Krewski et al. (2009) and value of a statistical life (VSL) to monetize mortality damages (Muller & Mendelsohn, 2007), supplemented by morbidity estimates and Monte Carlo uncertainty analysis. Third, we extrapolate per-cow damage to other dairy states using a population-density elasticity model, assessing the externality's economic magnitude and informing the design of corrective instruments.

Our central estimates indicate that New Mexico dairy CAFOs cause approximately 20.6 premature deaths annually and generate $217.66 million in monetized health damages (90% CI: $146.8–$297.6 million), more than 99% of which are attributable to unregulated NH_3 emissions. Morbidity costs add $0.74 million annually. Statewide damages equal approximately $646 per cow per year, with metro-sited farms imposing damages exceeding $1,000 per cow, more than double those of rural operations. External costs equal roughly 15% of aggregate dairy revenues. The geographic distribution of damages is systematically misaligned with dairy income: downwind communities bear transported $PM_{2.5}$ costs without receiving compensating dairy revenues.

New Mexico provides an appropriate and tractable setting for this analysis. The state hosts the highest stocking density of dairy operations in the US (Joshi & Wang, 2018; USDA, 2019), exhibits the geographic concentration and industrial-scale production increasingly characteristic of the national dairy sector, and has relatively low background $PM_{2.5}$ levels that facilitate attribution. At the same time, we are explicit about the limits of external validity. New Mexico's low population density, arid meteorology, and distinct regulatory environment make it, in some respects, a lower-bound case for per-farm damages. We address regional transferability through a population-density elasticity model applied to four comparison states, yielding national damage estimates of $10.1–$64.9 billion annually. This comparison reveals how population density mediates the relationship between emissions and health costs, with direct implications for where regulatory intervention is most warranted.

The paper proceeds as follows. Section 2 describes data and methods. Section 3 presents results. Section 4 discusses the distribution of damages and revenues, regional transferability, policy implications, and limitations. Section 5 concludes.

Data and Empirical Strategy

Our empirical strategy integrates farm-level emission estimation, atmospheric dispersion modeling and health impact valuation, following the standard damage-function approach (Muller and Mendelsohn, 2007; US EPA, 2014).

Dairy Farm Data and Emissions

Farm-level data for 2021 were compiled from the New Mexico Environment Department (NMED) Ground Water Discharge Permit database and the US Department of Agriculture (USDA) Census of Agriculture. The final dataset includes 132 large dairy CAFOs, representing approximately 337,000 dairy cows statewide (Table 1).

Because NMED permits do not report farm-specific cow inventories, we impute cow counts by allocating county-level USDA milk cow inventory to each farm in proportion to its permitted discharge volume. This proportional allocation assumes that discharge volume scales with herd size within each county, an approximation that introduces modest farm-level measurement error but preserves county-level consistency. The sum of imputed herd sizes differs from USDA county totals by less than 2%.

Table 1. Summary statistics for New Mexico dairy CAFOs (n = 132 farms, 2021).

	Total	Mean	Median	Std. Dev.	Max	Min
Dairy cows (heads)	337,000	2,553	1,946	2,056	10,853	128
NH_3 emissions (tons/year)	10,086	76	58	62	325	4
Primary $PM_{2.5}$ emissions (tons/year)	46	0.35	0.27	0.28	1.49	0.02

Emissions estimated using per-cow emission factors of 82 g NH_3/cow/day and 0.34 g $PM_{2.5}$/cow/day for arid Southwest conditions (Grant et al., 2020; Habib et al., 2022). County-level cow inventories from USDA (2022); farm locations and discharge volumes from NMED (2023).

Annual emissions E (kg/year) of pollutant $k \in \{NH_3, PM_{2.5}\}$ from farm i are calculated as:

(1) $$E_i^k = \eta^k \times x_i \times 365$$

Where η^k is the per-cow emission factor (kg/cow/day), and x_i is the herd size (number of dairy cows).

We use emission factors of 82g NH_3/cow/day and 0.34g primary $PM_{2.5}$/cow/day, drawn from studies of Western open-lot dairies under arid conditions (Grant, Boehm, and Hagevoort, 2020; Habib, Baticados, and Capareda, 2022). Sensitivity to these factors is examined in Section 2.6.

Each farm is classified into one of four location categories: metro, small metro, mixed, and rural, using US Census Bureau county designations and New Mexico Indicator-Based Information System (NMIBIS) (Census Bureau, 2023; NMIBIS, 2024).

Conceptual Framework

Dairy production generates emissions as a byproduct of output. Let farm i produce output q_i and generate emissions e_i, increasing in production and decreasing in abatement effort a_i.

(2) $$e_i = e(q_i, a_i), \frac{\partial e}{\partial q} > 0, \frac{\partial e}{\partial a} < 0$$

The private profit function is:

(3) $$\pi_i = p \cdot q_i - C(q_i, a_i)$$

where p is the milk price, $C(\cdot)$ denotes private production and abatement costs. Emissions generate external damages through secondary $PM_{2.5}$ formation. Total damage attributable to farm i is:

(4) $$D_i = \sum_j \tau_{ij} \cdot d_j \cdot e_i$$

where τ_{ij} is the source-receptor transport coefficient linking emissions from farm i to receptor location j, and d_j is marginal health damage at location r, determined by exposed population and baseline health risk. Social welfare is:

(5) $$W = \sum_i \pi_i + CS - \sum_i D_i$$

The first-best Pigouvian tax t_j^* equals marginal external damage:

(6) $$t_j^* = \frac{\partial D_i}{\partial e_i} = \sum_j \tau_{ij} \cdot d_j$$

Because transport coefficients and receptor population densities vary spatially, t_j^* differs across farms. This spatial heterogeneity motivates our use of a source–receptor model to estimate farm-specific marginal damages. The framework situates the analysis within the agricultural externality and pollution-pricing literature (Baumol and Oates, 1988; Shortle and Horan, 2001).

Atmospheric Transport Modeling

We use the InMAP Source-Receptor Matrix (ISRM) (Tessum, Hill, and Marshall, 2017) a reduced-form air quality model that provides annual-average concentration changes across 52,416 grid cells in the contiguous US The 132 dairy farms are assigned to 22 ISRM source grid cells based on geographic coordinates, and grid-level emissions are computed by summing farm-level emissions within each cell.

For each receptor grid cell r, the change in annual $PM_{2.5}$ concentration is:

$$\Delta C_r = \sum_s \tau_{rs} \cdot e_s \tag{7}$$

Where ΔC_r = change in annual mean $PM_{2.5}$ concentration (μg/m^3) at receptor r, τ_{rs} is the transport coefficient (μg/m^3 per ton emitted) mapping emissions from source cell s, to receptor r, and e_s is total emissions (tons/year) from source cell s.

This ISRM captures secondary inorganic aerosol formation, particularly the reaction of NH_3 with nitric and sulfuric acids to form ammonium nitrate and ammonium sulfate. This is critical because secondary formation accounts for the vast majority of agricultural $PM_{2.5}$ damages.

Health Impact Assessment

We apply a standard three-step damage function approach: (1) estimate concentration changes (ΔC_r), (2) apply CRFs, and (3) monetize health outcomes.

Mortality

Baseline mortality at receptor r is

$$\bar{M}_r = a_r \times \bar{\lambda}_r \tag{8}$$

where a_r is the exposed adult population and $\bar{\lambda}_r$ is the observed baseline all-cause mortality rate. Mortality changes are estimated using the log-linear CRF from Krewski et al. (2009):

$$\Delta M_r = \bar{M}_r(e^{\gamma \Delta C_r} - 1) \tag{9}$$

where $\gamma = 0.00583$ (95% CI: 0.00487–0.00679). Total attributable mortality is the sum across receptors.

Mortality is monetized using Environmental Protection Agency (EPA)'s central VSL of $10.52 million (2021 USD) consistent with EPA guidelines (US EPA, 2014).

Morbidity

To provide a more complete accounting of near-term health costs, we supplement the mortality damage function with morbidity endpoint estimates using EPA's Benefits Mapping and Analysis Program – Community Edition (BenMAP–CE) (US EPA, 2022). We estimate two primary morbidity endpoints: minor restricted activity days (MRAD, ages 18–65) and lost work days (LWD, ages 18–65). CRFs for each endpoint follow BenMAP–CE defaults: MRAD from Ostro and Rothschild (1989) and LWD from Ostro (1987).

We also evaluate four additional endpoints using BenMAP–CE default configurations: respiratory hospitalizations (ages 65+), cardiovascular hospitalizations (ages 65+), acute cough symptoms, and asthma emergency department visits. All four yield negligible central estimates, collectively less than $0.05 million annually, and are excluded from Table 2. Morbidity results are dominated by MRAD and LWD, which together account for over 99% of non-mortality health costs.

Table 2. Annual health damages by endpoint, 2021 dollars.

Endpoint	Annual Incidents	Unit Cost ($)	Annual Cost (M$) [95%CI]	% of Total
Mortality (ages 30+)	20.6 deaths	$10,520,000	216.92 [146.75, 297.56]	99.66%
Minor Restricted Activity Days (ages 18-65)	8,538 days	$70	0.60 [0.36, 0.84]	0.27%
Lost Work Days (ages 18-65)	690 days	$204	0.14 [0.08, 0.20]	0.06%
Subtotal: Morbidity			0.74 [0.47, 1.09]	0.34%
Total Health Costs			217.66 [137.94, 312.70]	100.00%

Note: Mortality estimated using Krewski et al. (2009) log-linear CRF ($\gamma = 0.00583$) and EPA VSL of $10.52 million. Morbidity endpoints estimated using BenMAP–CE default configurations; unit costs from AHRQ databases. Mortality CI from Monte Carlo simulation (n = 10,000); morbidity CIs reflect ±40% CRF uncertainty. NH_3 emissions account for 99.66% of mortality damages. Respiratory hospitalizations, cardiovascular hospitalizations, cough and asthma related endpoints were evaluated but excluded because aggregate costs were <0.01% of the mortality cost.

Sensitivity and Uncertainty Analysis

Four key parameters drive uncertainty in our damage estimates: the VSL, the mortality CRF coefficient γ, the NH_3 emission factor, and the primary $PM_{2.5}$ emission factor. We quantify this uncertainty through Monte Carlo simulation ($n = 10{,}000$ iterations), drawing all four parameters simultaneously from their established empirical distributions in each iteration.

Variance decomposition uses one-at-a-time analysis, varying each parameter independently while holding others at point estimates, to identify the relative contribution of each input to total output variance. This approach follows standard practice in health impact assessment uncertainty analysis (Roman et al., 2008; Hammitt and Robinson, 2011) and identifies which parameters would most repay further empirical investment. We report the median, 5th and 95th percentiles (90% CI), and coefficient of variation across simulations.

Population-Density Elasticity and Regional Transferability

To assess external validity, we estimate the elasticity of per-cow damages with respect to population density using the within-New Mexico InMAP results:

$$\ln(w_c) = \alpha + \beta \ln(\delta_c) + \varepsilon_c \tag{10}$$

where w_c is average per-cow marginal damage in county c, δ_c is county population density, and β captures how exposure intensity scales with receptor density.

This elasticity is applied to state-level population densities (Census Bureau, 2023) for California: 254; New York: 429; Wisconsin: 109; Idaho: 22; New Mexico: 18 persons per square mile, scaled by state dairy cow inventories (USDA, 2019), to construct indicative national damage extrapolations. We apply three extrapolation methods to bracket a plausible range of national damages. The first, simple scaling, multiplies New Mexico's aggregate damage estimate by the ratio of national to New Mexico dairy cow inventory. The second, population-adjusted scaling, applies the estimated density-damage elasticity to each state's population density and cow inventory, then sums across states. The third, a weighted top-five-state approach, computes state-specific per-cow damages for the five largest dairy states using the elasticity and applies New Mexico's baseline per-cow damage to remaining states. These methods provide lower-bound, preferred, and upper-bound national estimates, respectively.

These extrapolations assume comparable atmospheric chemistry, production systems and uniform population density across the state and should be interpreted as reduced-form approximations rather than structural predictions.

Results

This section presents four sets of findings: (1) spatial distribution of $PM_{2.5}$ concentration changes attributable to New Mexico dairy CAFOs; (2) total health damages, including mortality and morbidity; (3) sensitivity and uncertainty analysis; and (4) farm-level marginal damages and damage-to-revenue ratios by location category.

Emissions and Spatial Concentration Changes

In 2021, the 132 New Mexico dairy CAFOs emitted approximately 10,086 tons of NH_3 and 42 tons of primary $PM_{2.5}$ (Table 1). Applying the ISRM to these farm-level emissions yields measurable increases in annual mean $PM_{2.5}$ concentrations both within New Mexico and in downwind regions (Figure 1, Panel A). The most pronounced concentration increments occur near the primary dairy clusters in southeastern New Mexico. However, prevailing wind patterns produce a northward and eastward transport corridor, extending measurable concentration increases to receptor populations in eastern New Mexico, Texas, and the mid-Mississippi River Basin. This long-range transport implies that damages are not confined to communities adjacent to source farms.

NH_3 emissions account for over 99% of total monetized damages, reflecting the dominant role of secondary $PM_{2.5}$ formation relative to direct primary emissions (Figure 1, Panels B and C). Both pollutants exhibit long-range transport, but the scale of secondary $PM_{2.5}$ formation from NH_3 dwarfs direct $PM_{2.5}$ contributions. This distinction has direct policy implications: instruments targeting NH_3 reduction offer substantially greater health gains per dollar of abatement cost than primary PM controls in this setting.

Total Health Damages

Mortality

We estimate 20.6 annual premature deaths attributable to $PM_{2.5}$ from New Mexico dairy CAFOs, at a monetized mortality cost of $216.92 million per year (Table 2). Mortality accounts for 99.66% of total monetized health costs, consistent with prior regulatory assessments in which chronic mortality risk dominates acute clinical endpoints at diffuse, low-concentration exposures (Muller and Mendelsohn, 2007; Fann et al., 2012).

Morbidity

Total morbidity damages equal $0.74 million annually (95% CI: $0.47M–$1.09M), representing 0.36% of total health costs (Table 2). MRAD account for the majority at $0.60 million, reflecting high incidence but low per-case valuation, consistent with the epidemiological pattern of sub-clinical respiratory effects at diffuse $PM_{2.5}$ exposures (Ostro & Rothschild, 1989). LWD contribute an additional $0.14 million. Four additional endpoints evaluated via BenMAP–CE (respiratory hospitalizations, cardiovascular hospitalizations, acute cough, and asthma emergency department visits) collectively yield less than $0.05 million annually and are reported in the Table 2 note.

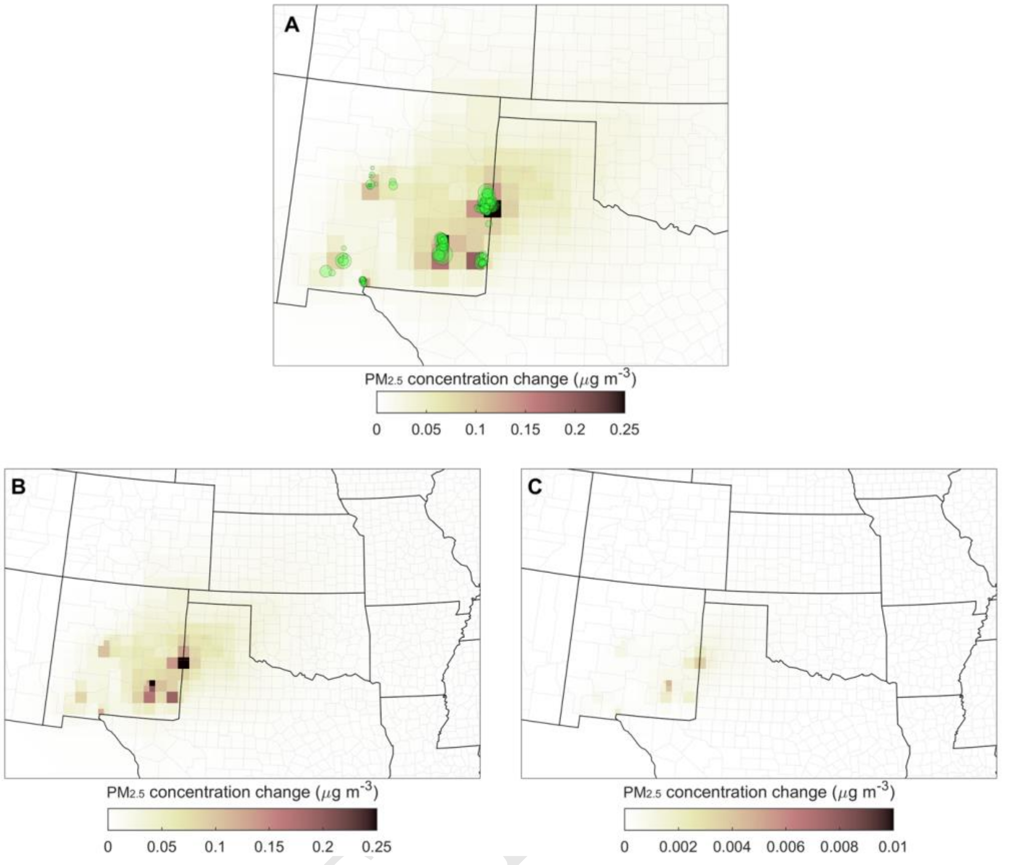

Figure 1. Annual mean $PM_{2.5}$ concentration change (μg/m^3) attributable to New Mexico dairy CAFO emissions, 2021.
Panel A: Total $PM_{2.5}$ increment across the contiguous US; green circles indicate CAFO locations scaled by herd size. Panel B: NH_3-derived (secondary) $PM_{2.5}$ component, and Panel C: Primary $PM_{2.5}$ component, illustrating substantial heterogeneity in the contribution of each towards total $PM_{2.5}$ concentration change. Modeled using the InMAP Source-Receptor Matrix (Tessum et al., 2017).

The dominance of mortality over morbidity is typical of $PM_{2.5}$ assessments at rural receptor populations, where diffuse exposure affects mortality risk distribution more than acute clinical outcomes (Fann et al., 2012). Because BenMAP–CE omits welfare-relevant dimensions such as psychological stress and pediatric developmental effects, the \$0.74 million figure is a conservative lower bound. Total annual health damages across both mortality and morbidity endpoints equal \$217.66 million (90% CI: \$137.94M–\$312.71M).

Sensitivity and Uncertainty Analysis

Figure 2 presents the Monte Carlo results (n = 10,000). Panel A shows the distribution of total annual health damages, which is approximately normal with a median of \$213.2 million and a 90% confidence interval of \$137.9 million to \$312.7 million (coefficient of variation: 21.4%).

Variance decomposition (Panel B) shows that VSL uncertainty accounts for 64.9% of total variance, followed by the NH_3 emission factor (20.8%), CRF coefficient γ (14.2%), and the primary $PM_{2.5}$ (~0%). This ordering is consistent with health impact assessment literature (Hammitt & Robinson, 2011; Roman et al., 2008) and implies that reducing uncertainty in VSL

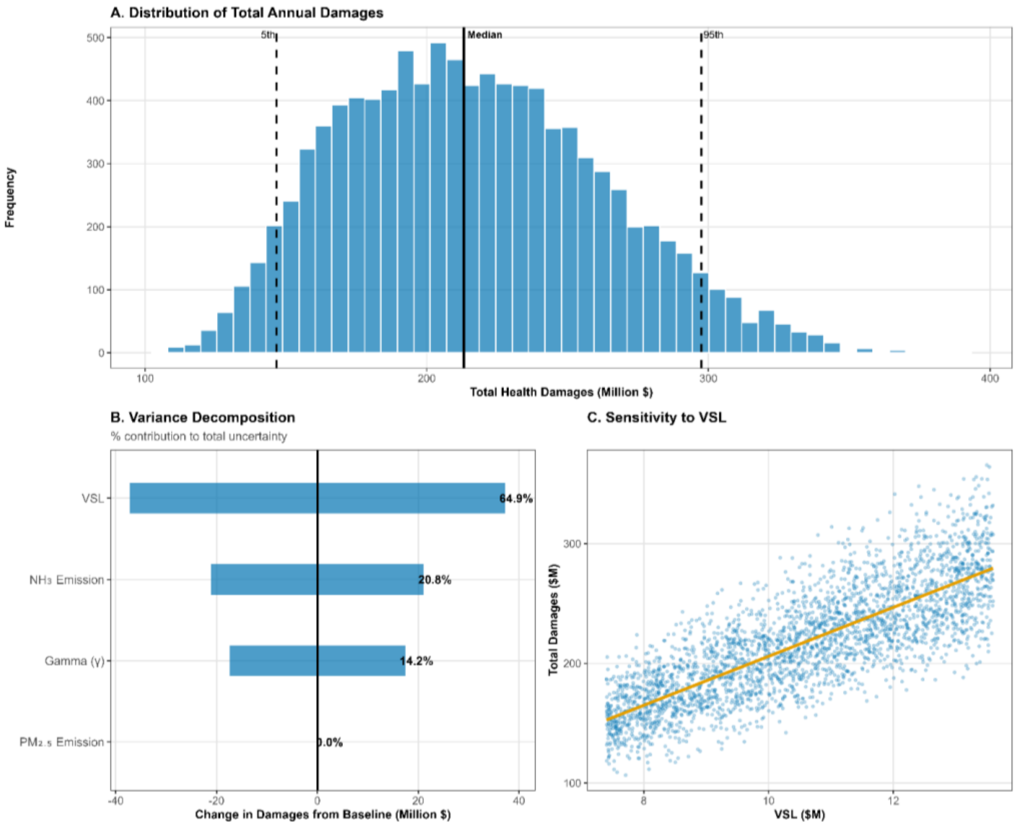

Figure 2. Monte Carlo sensitivity analysis (n = 10,000).
Panel A: Distribution of total annual health damages; vertical solid line = median ($213.2M), dashed lines = 5th and 95th percentiles ($137.9M and $312.7M). Panel B: Variance decomposition showing parameter's contribution to total output variance. Panel C: Scatterplot of VSL draws against total damages (Pearson r = 0.95). Parameter distributions reported in Table 2, Section 2.5.

estimates, through stated- or revealed-preference studies calibrated to the affected population, would most effectively narrow the damage range. Panel C confirms near-linear scaling of damages with VSL (Pearson r = 0.95), while emission factor correlations are substantially weaker (r ≈ 0.30–0.40).

Even at the 5th percentile of the simulated distribution, annual damages of $146.8 million exceed 11% of state dairy revenues, confirming that the finding of economically significant externalities is robust to parameter uncertainty.

Farm-Level Heterogeneity and Economic Significance

Table 3 reports per-cow marginal damages and damage-to-revenue ratios by urban-rural location category. The gradient across categories is large and monotonic. Metro-sited farms impose average damages of $1,086 per cow annually, more than double the $544 per cow at rural farms, reflecting the higher density of receptor populations downwind of farms near urban centers. Across all location categories, per-cow damages range from $464 to $1,621, with a statewide average of $646.

The damage-to-revenue ratio follows the same gradient. Compared to average gross dairy revenue per cow of approximately $4,315 (USDA, 2022), metro farms generate health costs

Table 3. Per-cow marginal health damage by location category, 2021 dollars.

Location Category	Total cows	Average farm size (cows)	Total health damages	Average damage per cow, $ per year	Damage-to-revenue ratio
Metro	5,319	1,330	5,796,504	1,086	25%
Small Metro	14,516	1,117	10,262,605	704	16%
Mixed	282,452	2,591	182,686,391	644	15%
Rural	34,712	5,785	18,954,500	544	13%

Notes: Average marginal damages by urban–rural location category (Census Bureau, 2023; NMIBIS, 2024). Metro-sited farms impose damages more than double those of rural operations. Average gross dairy revenue per cow: $4,315 (USDA, 2022).

equivalent to 25% of revenues, followed by small metro (16%), mixed (15%), and rural (13%). The statewide aggregate ratio of approximately 15%, roughly $0.15 in uncompensated health costs per dollar of dairy revenue, provides a first-order approximation of the Pigouvian fee rate needed to internalize the externality at the margin (Baumol & Oates, 1988).

Herd size is not a reliable proxy for social cost; per-cow damages are driven by proximity to populated areas rather than emission intensity. Because NH_3 disperses broadly before forming secondary $PM_{2.5}$, damage extends well beyond the source area and receptor populations with no direct economic stake in dairy production bear a substantial share of the health burden.

Regional Transferability and National Implications

The log-log regression of per-cow damages on county population density, estimated from the within-New Mexico InMAP results, yields an elasticity of 0.74 (SE = 0.09, $p < 0.001$, $R^2 = 0.92$), indicating that marginal damages increase sharply with receptor density. Applying this elasticity to four comparison states using state-level population densities and USDA cow inventories produces large cross-state variation in per-cow damage estimates (Figure 3). National extrapolation using three methods brackets total dairy air pollution damages between $10.1 billion (simple scaling) and $64.9 billion (upper-bound weighted top-5-state), with a preferred estimate of $33.4 billion annually. The limitations and interpretation are discussed in Section 4.3.

Discussion

This section interprets our damage estimates in four respects: their economic magnitude relative to production value and existing policy; the distribution of costs and revenues; the design of corrective instruments; and the limitations that qualify the analysis.

Magnitude and Economic Significance of the Externality

A foundational question in agricultural externality research is whether monetized damages are large enough to warrant corrective intervention (Shortle and Horan, 2001). Our results indicate they are. At $646 per cow statewide and $1,621 at the most exposed metro-adjacent farms (metro category average: $1,086), damages represent 11–25% of gross revenues per cow ($4,315; USDA, 2022). Affected populations are spatially disconnected from producers, precluding Coasean bargaining at the scale (Stavins, 2011; Coase, 2013).

Comparison with prior national estimates reinforces the scale of the problem. Domingo et al. (2021) estimate approximately $36 billion annually in health damages from all US agricultural NH_3. Our farm-level estimate implies damage intensity, reflecting New Mexico's prevailing wind patterns transporting emissions toward more densely populated receptor areas than is typical for arid-region sources. Goodkind et al. (2019), using a similar ISRM-based approach for agricultural

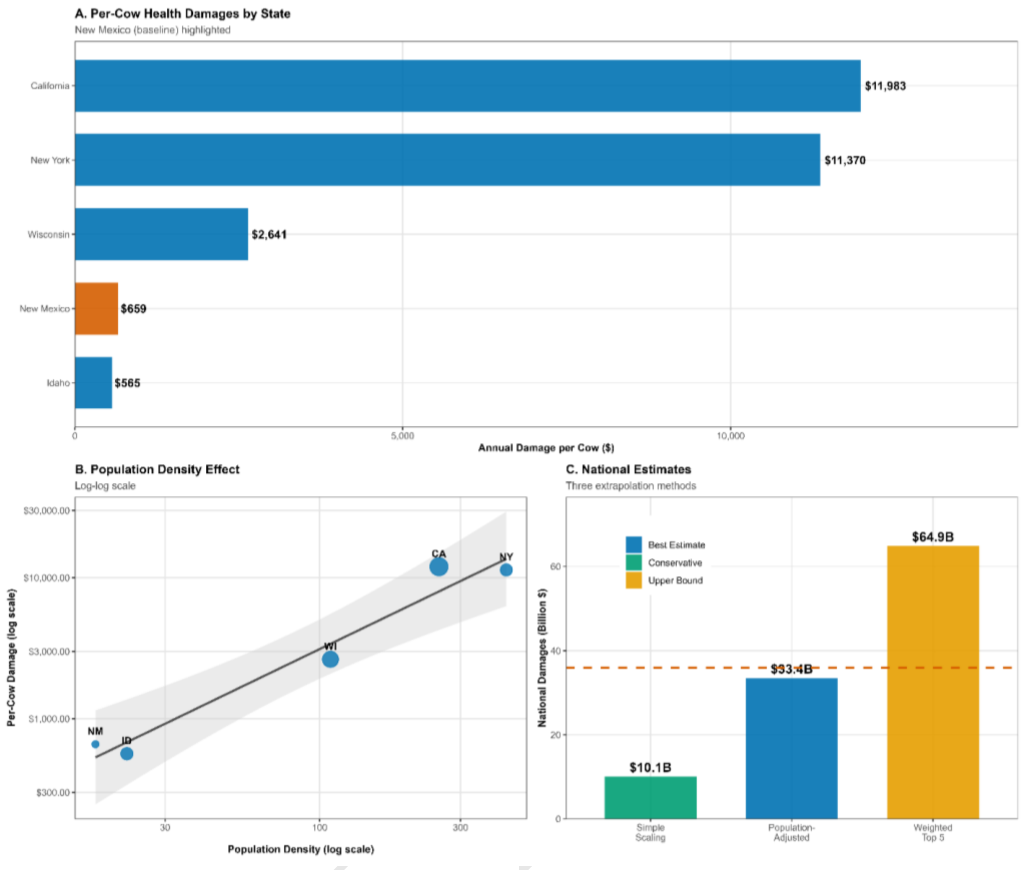

Figure 3. Regional transferability and national extrapolation.
Panel A: Per-cow annual health damage estimates for five dairy states; New Mexico (baseline) shown in orange. Panel B: Log-log relationship between county population density and per-cow damage, estimated from New Mexico data (R2 = 0.92); comparison states overlaid. Panel C: National damage estimates under three extrapolation methods (simple scaling, population-adjusted scaling, and weighted top-5-state approach) compared to the Domingo et al. (2021) benchmark of $36 billion for all agricultural NH3 (dashed line). All values in 2021 dollars.

emissions nationally, report a comparable gradient between low- and high-density production regions, supporting the plausibility of our estimates.

Federal dairy support programs such as Dairy Margin Coverage and Dairy Revenue Protection transfer several hundred million dollars annually to producers (MacDonald, Hoppe, and Newton, 2018). When these instruments subsidize production generating unpriced health costs, they create a double distortion. This does not imply support programs should be eliminated, but it does suggest that dairy policy should incorporate air pollution externalities into benefit-cost accounting.

Distribution of Damages and Revenues

The geographic distribution of damages is systematically misaligned with dairy revenues. Receptor populations in eastern New Mexico and downwind Texas bear transported $PM_{2.5}$ but receive no compensating dairy income, while dairy-producing counties in southeastern New Mexico receive revenue benefits but bear a smaller share of total health costs due to lower local population density. Table 3 quantifies this pattern: metro-area receptor populations bear per-cow damages of $1,086 annually, more than double the $544 per cow borne near rural facilities, yet dairy revenues accrue overwhelmingly to rural production counties. This spatial externality structure, where those bearing health costs are disconnected from those receiving production income, implies that source-sited regulation alone is insufficient and that downwind jurisdictions have a legitimate interest in emission controls at upwind operations.

Formal linkage between receptor-level exposure and Census tract demographics is not feasible, because ISRM grid cells do not align with Census boundaries. Reconciling the two through areal interpolation or population-weighted reassignment would introduce substantial uncertainty. We note, however, that the communities most proximate to New Mexico dairy CAFOs are disproportionately low-income and Hispanic. The national-average VSL applied here may understate damages in equity-weighted terms (Hammitt and Robinson, 2011; Viscusi, 2018). Distributional VSL adjustments and formal environmental justice assessment of CAFO air pollution exposure represent important priorities for future research using harmonized spatial data.

Regional Transferability

Although this analysis focuses on New Mexico, the results illustrate a general principle: the economic consequences of agricultural air pollution are shaped primarily by the density of downwind receptor populations. Using a population-density elasticity of per-cow damages (0.74, $R^2 = 0.92$) estimated from within-state variation, we extrapolate indicative damage estimates to four comparison states (Figure 3). Per-cow damages rise sharply in more densely populated regions, with estimates for California and New York exceeding New Mexico's baseline by an order of magnitude. National extrapolations bracket a range of $10.1–$64.9 billion, with the population-adjusted preferred estimate of $33.4 billion.

These extrapolations are illustrative rather than definitive. Statewide population density likely overstates receptor exposure for California and New York, where dairy operations concentrate in lower-density agricultural regions. Differences in meteorology, atmospheric chemistry, and regulatory environments further limit direct comparability, and farm-level InMAP modeling within each state would substantially improve precision. Nevertheless, even the most conservative extrapolation implies national damages of several billion dollars annually, and the core finding, that uniform emission standards are inefficient when damages vary by an order of magnitude across locations (Muller and Mendelsohn, 2009), does not depend on the exact national figure.

Policy Implications

Pricing Agricultural Air Pollution

The damage estimates in this paper provide empirical inputs to evaluate Pigouvian instruments in agriculture. Standard theory prescribes setting emission fees equal to marginal external damage at the social optimum (Pigou, 1920; Baumol and Oates, 1988). In practice, because marginal damages vary across source locations by an order of magnitude (Table 3), a uniform national fee would be inefficient, over-regulating low-damage rural sources while under-regulating high-damage peri-urban ones (Muller and Mendelsohn, 2009). A location-differentiated fee calibrated to per-cow damage estimates would be theoretically first-best but requires administrative infrastructure currently absent from US agricultural regulation.

A pragmatic second-best instrument is a regionally differentiated performance standard, analogous to non-attainment area designations under the Clean Air Act, imposing stricter NH_3 limits in high-population-density dairy regions. The European Union's National Emission

Ceilings Directive demonstrates feasibility, with Giannakis et al. (2019) documenting benefit–cost ratios exceeding four-to-one. The key policy enabler in these international models was formal recognition of NH_3 as a regulated precursor pollutant, a designation the EPA has resisted for agricultural sources, despite the efficiency case presented here.

Siting and Spatial Policy Design

Because damages are driven by proximity to receptor populations, siting standards offer a complement emission rate controls. Metro-sited CAFOs impose per-cow damages more than double those of rural operations (Table 3), yet CAFO permitting under the Clean Water Act does not incorporate air quality exposure. Incorporating air quality impact assessments to permitting would allow regulators to direct new operations toward lower-exposure locations. Market-based complements such as transferable development rights could reinforce siting incentives (Stavins, 2011). Reform of Right to Farm statutes to distinguish agricultural protection from externality immunity would further support efficient land-use decisions (Diamond et al., 2022).

Emission Reduction and Technology Incentives

For existing operations where relocation is infeasible, source-level abatement remains important. Diet modification and improved manure management yield the largest NH_3 reductions at lowest cost (Ndegwa et al., 2008; Hou, Velthof, and Oenema, 2015). Anaerobic digestion achieves joint reductions in NH_3, methane, and primary PM, and may be cost-effective at scale given USDA support (Joshi and Wang, 2018). However, abatement policies must account for pollutant interactions as practices reducing NH_3 may increase methane or nitrous oxide under certain conditions (Hou, Velthof, and Oenema, 2015; UNECE, 2021), favoring integrated whole-farm emission accounting.

Interagency Coordination and Monitoring

Effective NH_3 regulation requires coordination between EPA and USDA, whose objectives can conflict: USDA manure management programs may encourage open lagoon storage that exacerbates air emissions, while EPA's clean air programs rarely extend to agricultural NH_3 sources (Wang and Baerenklau, 2015). The Fair Agricultural Reporting Method Act of 2018 compounded existing gaps by exempting farms from NH_3 reporting. Restoring these requirements is a necessary precondition for incentive-based or performance-standard approach, since neither can be administered without credible emission measurement (Berck, 2018).

Limitations and Future Research

Several limitations qualify our estimates. First, the analysis quantifies only $PM_{2.5}$-mediated health damages from NH_3 and primary PM emissions. Other pollutants from dairy CAFOs, including hydrogen sulfide, volatile organic compounds, bioaerosols, and odor, as well as water quality and ecosystem damage from nutrient runoff are excluded. The $217.66 million annual estimate is therefore a partial, conservative lower bound on total external costs.

Second, emission factors are drawn from prior literature calibrated to similar arid-Southwest conditions rather than direct measurements from New Mexico facilities. Monte Carlo analysis confirms that emission factor uncertainty contributes 21% of total output variance, modest relative to VSL uncertainty (64.9%). Nevertheless, farm-level measurement campaigns analogous to those conducted by Grant et al. (2020) for Western open-lot dairies would improve the precision of source attribution.

Third, the spatial resolution of the ISRM grid does not permit formal linkage between pollution exposure and Census tract-level demographic characteristics. Harmonizing these spatial frameworks through dasymetric mapping or population-weighted areal interpolation would enable rigorous environmental justice assessment and represents a methodological priority for future research.

Fourth, the transferability extrapolations rely on a reduced-form relationship between population density and per-cow damage estimated from within-New Mexico variation. While internally plausible (R^2 = 0.92), extrapolation uncertainty increases at the tails of the density distribution, and differences in meteorology and atmospheric chemistry across states cannot be verified without additional modeling. State-level InMAP analyses for California and Wisconsin, where refined estimates would most alter the national damage picture, represent the highest-value extension of this research.

Conclusion

This study quantifies the health damages from dairy CAFO air emissions in New Mexico using farm-level atmospheric dispersion modeling and established epidemiological and economic valuation methods. Our central estimates indicate 20.6 premature deaths and $217.66 million in annual health costs (90% CI: $146.8–$297.6 million), with over 99% of damages attributable to secondary $PM_{2.5}$ formed from unregulated NH_3 emissions. These costs equal approximately 15% of the state's aggregate dairy revenues. The spatial distribution of damages is driven by receptor population density, with per-cow damages ranging from $544 at rural operations to $1,086 near metro areas. Population-adjusted extrapolation to other major dairy states yields national damage estimates of $10.1–64.9 billion annually (preferred estimate: $33.4 billion), suggesting that the New Mexico case represents a lower bound.

The results carry several policy implications. First, the order-of-magnitude variation in per-cow damages across location categories demonstrates that uniform emission standards would be inefficient. Location-differentiated instruments, whether Pigouvian fees calibrated to marginal damages or regionally differentiated performance standards, are better suited to the spatial structure of the externality. Second, the current exemption of agricultural NH_3 from federal reporting requirements under the FARM Act prevents the emission measurement necessary for any incentive-based or standard-based approach. Restoring these reporting requirements would be a low-cost prerequisite for efficient regulation. Third, the systematic misalignment between where damages fall and where dairy revenues accrue underscores the need for regulatory frameworks that account for downwind exposure, including air quality criteria in CAFO siting and permitting.

Several extensions would strengthen the analysis. Farm-level emission measurements would reduce the biophysical uncertainty that limits source attribution precision. Harmonizing the ISRM grid with Census tract boundaries would enable formal environmental justice assessment of exposure burdens. State-level InMAP analyses for California and Wisconsin, where population densities substantially exceed New Mexico's, would sharpen the national damage picture. Finally, the estimates presented here capture only $PM_{2.5}$-mediated health damages and exclude other externalities including water quality degradation, ecosystem effects, and worker health impacts, reinforcing that the $217.66 million figure should be interpreted as a conservative partial estimate of the total social cost of dairy air pollution.

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