

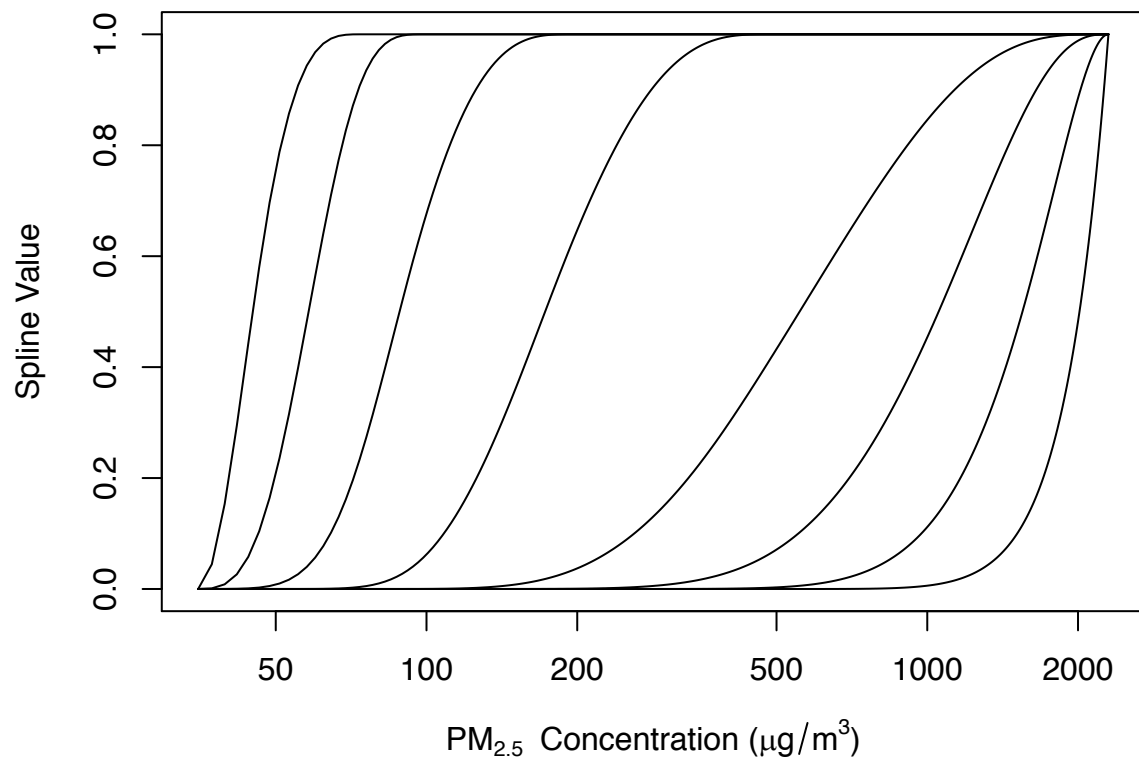
Supplementary Digital Content

A Hierarchical Model for Estimating the Exposure-Response Curve by Combining Multiple Studies of Acute Lower Respiratory Infections in Children and Household Fine Particulate Matter Air Pollution

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eFigure 1: I-Splines for the combined analysis of the three Nepal studies., using boundary knots at 25 and 2,300 $\mu\text{g}/\text{m}^3$ and interior knots at 50, 75, 100, 200, and 500 $\mu\text{g}/\text{m}^3$.



eAppendix 1: Exposure Model Settings for Nepal Studies

In the primary model for the Bhaktapur Study, no information was available about household clustering, so no cluster-random effect was included. Because there was only a single PM_{2.5} measurement per household in the Bhaktapur and Sarlahi II studies, we used an informative prior for the within-household random effect standard deviation (σ_H) that was informed by the results of the Sarlahi I study (eTable 1).

eTable 1: Values and distributions for parameters, hyperparameters, and hyperpriors for the Bhaktapur exposure model.

Quantity	Bhaktapur Primary Exposure Model	Bhaktapur Exposure Sensitivity Model 1	Bhaktapur Exposure Sensitivity Model 2
τ	7 days	7 days	7 days
df	4	4	4
η_0	4	4	4
σ_G	$N_+(0, 1)$	$N_+(0, 1)$	$N_+(0, 1)$
σ_H	$N_+(0.5, 0.1)$	$N_+(0, 0.1)$	$N_+(0, 1)$
σ_W	$N_+(0, 1)$	$N_+(0, 1)$	$N_+(0, 0.1)$
σ_θ	$N_+(0, 1)$	$N_+(0, 1)$	$N_+(0, 1)$
Number of Post-Warmup Iterations	2,000	2,000	2,000
Number of Chains	10	10	10

eTable 2: Values and distributions for parameters, hyperparameters and hyperpriors for the Sarlahi exposure models.

Quantity	Sarlahi I	Sarlahi II
τ	7 days	7 days
df	9	4
η_0	6	5
σ_G	$N_+(0, 1)$	$N_+(0, 1)$
σ_H	$N_+(0, 0.5)$	$N_+(0.3, 0.1)$
σ_K	$N_+(0.1, 0.5)$	$N_+(0, 0.5)$
σ_W	$N_+(0, 0.1)$	$N_+(1, 0.1)$
σ_θ	$N_+(0, 0.5)$	$N_+(0, 1)$
Number of Post-Warmup Iterations	1,000	1,000
Number of Chains	8	8

eAppendix 2 Exposure-Response Model Setting for Nepal Studies

For computing long-term exposures x_{sit} , we set $\tilde{T} = 28$ days. This has practical impact only for Sarlahi I, because that study included crossover across stove groups. This allows for a piece-wise linear transition in the estimated long-term average exposure concentrations from the traditional stove to the improved biomass stove. This time period is also short enough that it provides for meaningful contrasts in exposure in the amount of follow-up time available after stove intervention, which ranged from 6 to 12 months. For all studies we aggregated the health data to 28-day increments, in order to reduce the computational burden (with this resolution the total number of observations, including repeated measures, is 83,932). The time at risk, T_{sit} , for the Sarlahi studies was calculated as the total number of days in each follow-up period when not in an ALRI episode or on the first day of an ALRI episode. In the Bhaktapur study, the time at risk for each individual was set to 1, as is done in logistic regression. For the Sarlahi models, we used temporal splines with approximately 1 df for every three months of study period (eTables 3-5).

eTable 3: Values and distributions for parameters, hyperparameters and hyperpriors for the Bhaktapur exposure-response model.

Quantity	Primary Exposure- Response Model	Exposure- Response Sensitivity Model 1	Exposure- Response Sensitivity Model 2	Exposure- Response Sensitivity Model 3	Exposure- Response Sensitivity Model 4
$\tilde{T}$	--	--	--	--	--
v_s	0	0	0	0	0
β_0	0	0	0	0	0
σ_β	N ₊ (0.5, 0.1)	N ₊ (0.5, 0.1)	N ₊ (0.5, 0.1)	N ₊ (0.5, 0.1)	N ₊ (0.5, 0.1)
σ_ξ	N ₊ (0.1, 0.1)	N ₊ (0.1, 0.1)	N ₊ (0.1, 0.1)	N ₊ (0.1, 0.1)	N ₊ (0.1, 0.1)
σ_Γ	N ₊ (0, 1)	N ₊ (0, 1)	N ₊ (0, 1)	N ₊ (0, 1)	N ₊ (0, 1)
σ_Δ	--	--	--	--	--
Model for x_{sit}	Bhaktapur Primary Exposure Model	Bhaktapur Exposure Sensitivity Model 1	Bhaktapur Exposure Sensitivity Model 2	Observations	Bhaktapur Primary Exposure Model
Exposure- Response Spline					
β non-negative	No	No	No	No	Yes
Boundary knots	35, 820	50, 500	20, 2100	11, 8000	35, 820
Internal knots	45, 65, 100, 200	55, 10	45, 65, 100, 200	45, 65, 100, 200	45, 65, 100, 200

eTable 4: Values and distributions for parameters, hyperparameters and hyperpriors for the Sarlahi exposure-response models.

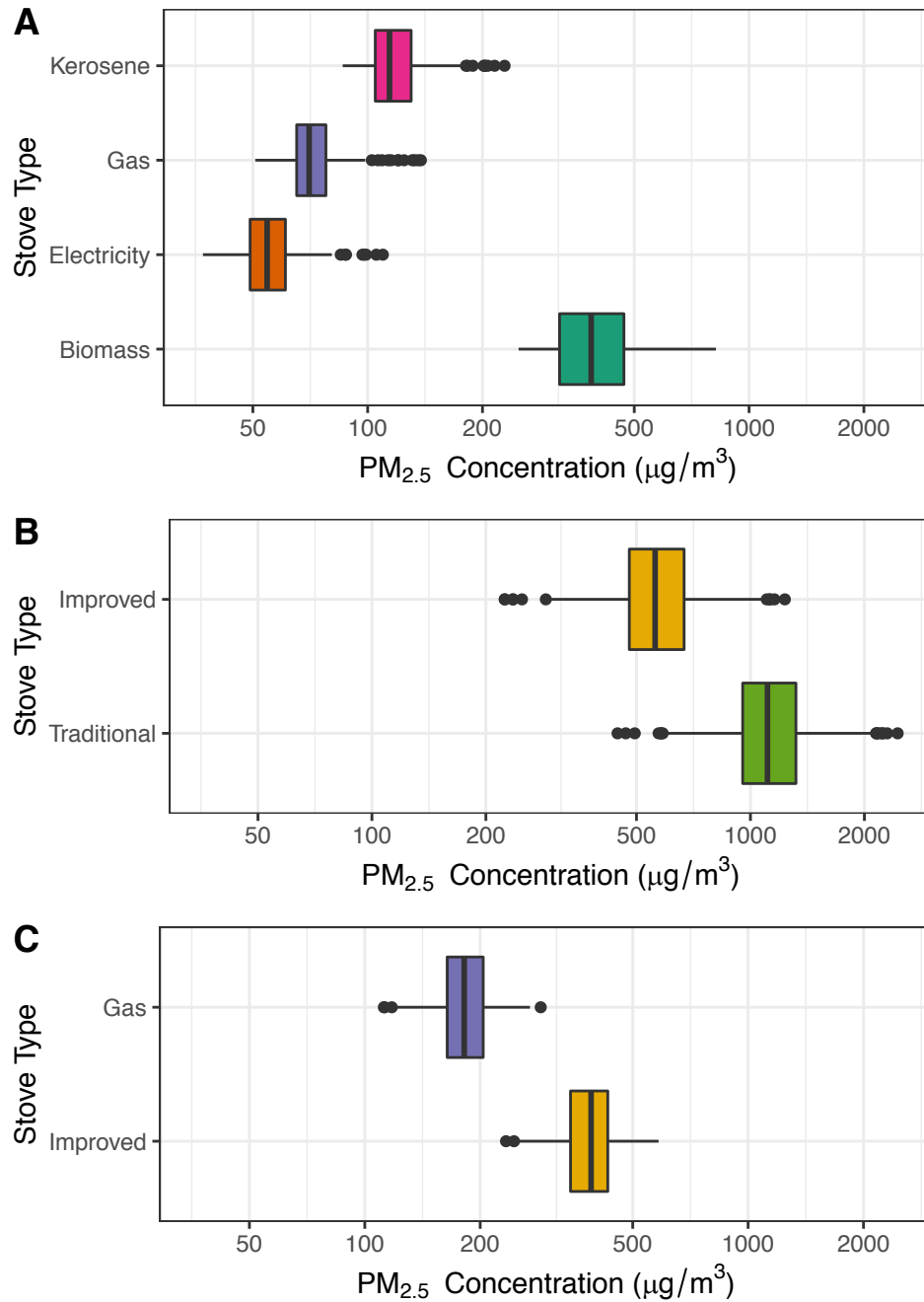
Quantity	Sarlahi I	Sarlahi II
$\tilde{T}$	28 days	--
v_s	8	4
β_0	0	0
σ_β	$N_+(0, 1)$	$N_+(0, 0.5)$
σ_ξ	$N_+(0, 1)$	$N_+(0.5, 0.5)$
σ_Γ	$N_+(0, 1)$	$N_+(0, 0.5)$
σ_Δ	$N_+(0, 1)$	$N_+(0, 0.5)$
Exposure-Response Spline		
β non-negative	No	No
Boundary knots	224, 2298	111, 590
Internal knots	None	None

eTable 5: Values and distributions for parameters, hyperparameters and hyperpriors for the combined exposure-response models.

Quantity	Primary Model	Non-decreasing Sensitivity Model
$\tilde{T}$	28 days	28 days
$v_{Bhaktapur}$	0	0
$v_{Sarlahi I}$	8	8
$v_{Sarlahi II}$	4	4
β_0	0	0
σ_β	$N_+(0.5, 1)$	$N_+(0.5, 1)$
σ_ξ	$N_+(0.5, 0.5)$	$N_+(0.5, 0.5)$
σ_Γ	$N_+(0, 0.5)$	$N_+(0, 0.5)$
σ_Δ	$N_+(1, 0.5)$	$N_+(1, 0.5)$
Exposure-Response Spline		
β non-negative	No	Yes
Boundary knots	35, 2300	35, 2300
Internal knots	50, 75, 100, 200, 500	50, 75, 100, 200, 500

eAppendix 3 Results for Exposure Concentration Models

eFigure 2: Modeled long-term concentrations from (A) Bhaktapur study, (B) Sarlahi I, and (C) Sarlahi II.



eTable 6: Summary statistics of the modelled long-term average PM_{2.5} concentrations (µg/m³) for each household in each study, by primary stove type (Bhaktapur) and assigned stove type (Sarlahi studies).

Study	Stove Type	N	Geo. Mean	Min	Q25	Median	Q75	Max	Mean	Std. Dev.
Bhaktapur	Biomass	218	390	249	318	386	470	819	403	108
	Kerosene	187	119	86	105	114	130	228	121	26
	Gas	238	72	51	65	70	78	138	74	14
	Electricity	181	55	37	49	54	61	110	56	12
Sarlahi Phase I	Traditional Biomass	3351	1122	446	954	1110	1322	2448	1155	281
	Improved Biomass	3342	566	224	480	560	667	1233	582	142
Sarlahi Phase II	Improved Biomass	659	384	232	343	389	431	590	389	65
	Gas	661	182	111	164	182	204	289	184	30

Note: Geo. Mean: Geometric mean; Q25: 25th percentile; Q75: 75th percentile; Std. Dev.: standard deviation.

eTable 7: Posterior means (95% credible interval) for all parameters in the Bhaktapur exposure concentration models.

Parameters	Primary Model	Sensitivity Model 1	Sensitivity Model 2
Biomass (η_1)	5.96 (5.85, 6.08)	5.96 (5.85, 6.08)	5.96 (5.85, 6.08)
Kerosene (η_2)	4.78 (4.66, 4.90)	4.78 (4.66, 4.90)	4.79 (4.67, 4.91)
Gas (η_3)	4.28 (4.18, 4.39)	4.28 (4.18, 4.39)	4.29 (4.18, 4.39)
Electricity (η_4)	4.01 (3.89, 4.13)	4.01 (3.89, 4.13)	4.02 (3.90, 4.14)
Time Spline 1 (θ_1)	-0.03 (-0.30, 0.20)	-0.03 (-0.30, 0.20)	-0.03 (-0.30, 0.20)
Time Spline 2 (θ_2)	0.26 (0.00, 0.56)	0.25 (-0.01, 0.55)	0.25 (-0.01, 0.55)
Time Spline 3 (θ_3)	-0.21 (-0.82, 0.22)	-0.20 (-0.81, 0.22)	-0.20 (-0.81, 0.22)
Time Spline 4 (θ_4)	-0.10 (-0.37, 0.13)	-0.10 (-0.36, 0.13)	-0.10 (-0.36, 0.13)
σ_G	1.15 (0.64, 2.02)	1.15 (0.64, 2.04)	1.15 (0.64, 2.04)
σ_I	0.41 (0.24, 0.56)	0.08 (0.00, 0.21)	0.08 (0.00, 0.21)
σ_W	0.71 (0.60, 0.79)	0.81 (0.77, 0.89)	0.81 (0.77, 0.89)
σ_θ	0.32 (0.05, 0.90)	0.31 (0.05, 0.89)	0.31 (0.05, 0.89)

eTable 8: Summary statistics of the modelled PM_{2.5} concentrations (µg/m³) for the sensitivity analyses for the Bhaktapur exposure concentration model.

Model	Stove Type	N	Geometric Mean	Min	Q25	Median	Q75	Max	Mean	Std. Dev.
Sensitivity Model 1	Biomass	218	389	380	385	389	393	404	389	5.3
	Kerosene	187	119	116	118	118	119	123	119	1.2
	Gas	238	72	71	72	72	73	75	72	0.7
	Electricity	181	55	54	55	55	56	57	5	0.6
Sensitivity Model 2	Biomass	218	393	142	248	383	598	2091	467	307
	Kerosene	187	119	57	89	108	145	527	133	76
	Gas	238	73	32	57	68	84	310	80	43
	Electricity	181	55	22	43	53	69	260	62	36

Note: Q25: 25th percentile; Q75: 75th percentile; Std. Dev.: standard deviation.

eTable 9: Posterior means (95% credible interval) for all parameters in the Sarlahi Phase 1 exposure concentration model.

Parameter	Posterior Mean (95% Credible Interval)
Traditional Biomass (η_1)	7.03 (6.87, 7.19)
Improved Biomass (η_2)	6.35 (6.22, 6.49)
Time Spline 1 (θ_1)	-1.26 (-1.59, -0.93)
Time Spline 2 (θ_2)	0.29 (-0.13, 0.71)
Time Spline 3 (θ_3)	-0.48 (-0.85, -0.13)
Time Spline 4 (θ_4)	-0.96 (-1.56, -0.43)
Time Spline 5 (θ_5)	-0.18 (-0.73, 0.34)
Time Spline 6 (θ_6)	0.43 (-0.08, 0.90)
Time Spline 7 (θ_7)	0.15 (-0.30, 0.56)
Time Spline 8 (θ_8)	-1.57 (-2.44, -0.78)
Time Spline 9 (θ_9)	-0.39 (-0.85, 0.05)
σ_G	0.95 (0.41, 2.00)
σ_K	0.21 (0.16, 0.27)
σ_I	0.30 (0.26, 0.34)
σ_W	0.71 (0.69, 0.72)
σ_θ	0.80 (0.49, 1.24)

eTable 10: Posterior means (95% credible interval) for all parameters in the Sarlahi Phase II exposure concentration model.

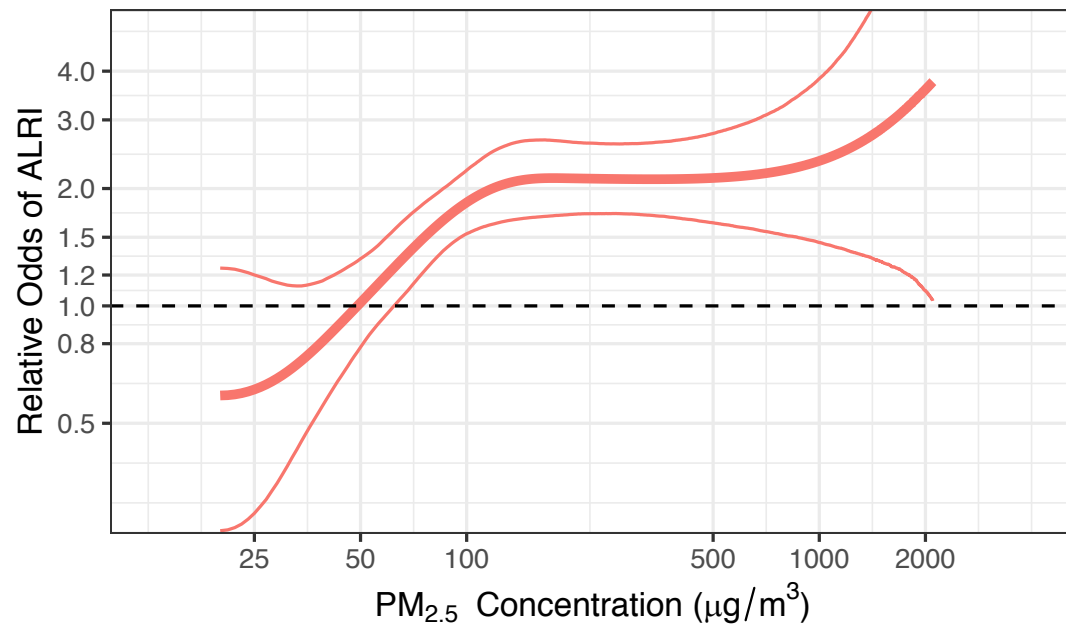
Parameter	Posterior Mean (95% Credible Interval)
Improved Biomass (η_2)	5.97 (5.73, 6.22)
Gas (η_3)	5.22 (4.99, 5.47)
Time Spline 1 (θ_1)	-0.63 (-1.37, 0.09)
Time Spline 2 (θ_2)	2.17 (1.31, 3.06)
Time Spline 3 (θ_3)	-0.92 (-2.73, 0.84)
Time Spline 4 (θ_4)	-2.71 (-4.35, -0.95)
σ_G	0.92 (0.37, 1.98)
σ_K	0.20 (0.12, 0.29)
σ_I	0.25 (0.08, 0.42)
σ_W	0.88 (0.81, 0.93)
σ_θ	1.67 (0.86, 2.73)

eAppendix 4 Results for Exposure-Response Models

eTable 11: Posterior Means (95% Credible Intervals) for all parameters from the Bhaktapur exposure-response models

Quantity	Primary Model	Exposure- Response Sensitivity 1	Exposure- Response Sensitivity 2	Exposure- Response Sensitivity 3	Exposure- Response Sensitivity 4
ψ_s	-1.17 (-2.11, -0.29)	-0.58 (-0.99, -0.19)	-1.09 (-1.88, -0.33)	-0.94 (-1.47, -0.45)	-1.23 (-2.06, -0.60)
β_1	0.45 (-0.46, 1.44)	0.52 (0.00, 1.05)	0.31 (-0.53, 1.19)	0.34 (-0.32, 1.03)	0.52 (0.03, 1.33)
β_2	0.39 (-0.30, 1.07)	0.37 (-0.33, 1.13)	0.41 (-0.25, 1.10)	0.35 (-0.26, 0.97)	0.46 (0.04, 1.02)
β_3	0.63 (0.09, 1.21)	-0.15 (-0.96, 0.60)	0.57 (0.07, 1.07)	0.41 (-0.08, 0.90)	0.32 (0.03, 0.70)
β_4	-0.24 (-0.95, 0.42)	-0.17 (-1.04, 0.67)	-0.06 (-0.75, 0.60)	0.01 (-0.64, 0.64)	0.10 (0.00, 0.33)
β_5	-0.13 (-0.96, 0.69)	-0.03 (-1.04, 0.94)	0.14 (-0.76, 1.06)	0.31 (-0.34, 1.05)	0.13 (0.00, 0.41)
β_6	0.28 (-0.61, 1.22)	--	0.26 (-0.69, 1.29)	-0.27 (-0.90, 0.24)	0.26 (0.01, 0.76)
β_7	0.31 (-0.65, 1.36)	--	0.22 (-0.74, 1.26)	0.02 (-0.56, 0.63)	0.41 (0.02, 1.16)
Male (γ_1)	0.04 (-0.04, 0.16)	0.04 (-0.05, 0.16)	0.04 (-0.05, 0.16)	0.03 (-0.05, 0.15)	0.04 (-0.05, 0.16)
Age 7 to 12 months (γ_2)	0.02 (-0.07, 0.14)	0.03 (-0.06, 0.15)	0.02 (-0.07, 0.14)	0.02 (-0.07, 0.13)	0.02 (-0.06, 0.14)
Age 13 to 18 months (γ_3)	0.01 (-0.09, 0.12)	0.01 (-0.08, 0.12)	0.01 (-0.08, 0.12)	0.01 (-0.08, 0.12)	0.01 (-0.08, 0.12)
Age 19 to 24 months (γ_4)	-0.05 (-0.20, 0.03)	-0.05 (-0.19, 0.03)	-0.05 (-0.20, 0.03)	-0.05 (-0.20, 0.03)	-0.05 (-0.20, 0.03)
Age 25 to 36 months (γ_5)	0.00 (-0.1, 0.1)	0.00 (-0.10, 0.10)	0.00 (-0.09, 0.10)	0.01 (-0.09, 0.11)	0.00 (-0.10, 0.11)
σ_β	0.52 (0.35, 0.71)	0.50 (0.31, 0.69)	0.51 (0.23, 0.70)	0.48 (-0.31, 0.66)	0.47 (0.30, 0.66)
σ_ξ	0.13 (0.01, 0.30)	0.13 (0.01, 0.30)	0.13 (0.01, 0.30)	0.13 (0.01, 0.30)	0.13 (0.01, 0.30)
σ_Γ	0.07 (0.00, 0.22)	0.07 (0.0, 0.22)	0.07 (0.00, 0.22)	0.07 (0.00, 0.22)	0.07 (0.00, 0.22)

eFigure 3: Bhaktapur Sensitivity Model 2 exposure-response curve (posterior mean with pointwise 95% credible intervals).



eTable 12: Posterior Means (95% Credible Intervals) from the Sarlahi I exposure-response model.

Quantity	Posterior Mean (95% Credible Interval)
ψ_s	-8.81 (-9.06, -8.60)
β_1	0.11 (-0.42, 0.84)
β_2	-0.05 (-0.99, 0.96)
β_3	-0.37 (-2.30, 0.42)
δ_1	-1.17 (-1.58, -0.76)
δ_2	-0.10 (-0.62, 0.41)
δ_3	-2.09 (-2.68, -1.52)
δ_4	0.70 (0.13, 1.25)
δ_5	-3.10 (-3.92, -0.39)
δ_6	-1.03 (-1.88, -0.16)
δ_7	-1.76 (-2.65, -0.91)
δ_8	-3.36 (-4.68, -2.22)
Female (γ_1)	-0.09 (-0.18, 0.01)
Age 4 to 7 months (γ_2)	0.12 (0.04, 0.20)
Age 8 to 12 months (γ_3)	0.03 (-0.06, 0.12)
Age 13 to 24 months (γ_4)	-0.20 (-0.32, -0.08)
Age 25 to 36 months (γ_5)	-0.53 (-0.68, -0.39)
σ_β	0.49 (0.01, 1.72)
σ_ξ	1.26 (1.14, 1.39)
σ_Γ	0.36 (0.17, 0.76)
σ_Δ	1.85 (1.22, 2.73)

eTable 13: Posterior Means (95% Credible Intervals) from the Sarlahi II exposure-response model.

Quantity	Posterior Mean (95% Credible Interval)
ψ_s	-9.46 (-10.30, -8.82)
β_1	0.01 (-0.60, 0.68)
β_2	-0.07 (-0.96, 0.61)
β_3	-0.07 (-1.02, 0.71)
δ_1	-0.03 (-1.06, 0.97)
δ_2	-1.76 (-3.63, -0.22)
δ_3	-0.59 (-2.45, 0.80)
δ_4	-0.27 (-1.73, 1.15)
Female (γ_1)	-0.04 (-0.27, 0.13)
Age 4 to 7 months (γ_2)	0.05 (-0.13, 0.30)
Age 8 to 12 months (γ_3)	0.04 (-0.15, 0.30)
Age 13 to 24 months (γ_4)	-0.02 (-0.26, 0.20)
σ_β	0.31 (0.01, 0.94)
σ_ξ	0.88 (0.12, 1.55)
σ_Γ	0.13 (0.00, 0.44)
σ_Δ	0.89 (0.27, 1.56)

eTable 14: Posterior Means (95% Credible Intervals) from the combined exposure-response models.

Study	Quantity	Primary Model	Non-Decreasing Model
Bhaktapur	ψ_1	-1.77 (-3.25, -0.54)	-1.15 (-2.13, -0.40)
	Male (γ_1)	0.22 (-0.11, 0.56)	0.20 (0.11, 0.77)
	Age 7 to 12 months (γ_2)	0.13 (-0.29, 0.55)	0.14 (-0.27, 0.57)
	Age 13 to 18 months (γ_3)	0.05 (-0.37, 0.48)	0.06 (-0.38, 0.48)
	Age 19 to 24 months (γ_4)	-0.34 (-0.81, 0.12)	-0.34 (-0.82, 0.11)
	Age 25 to 36 months (γ_5)	0.01 (-0.45, 0.47)	0.02 (-0.46, 0.49)
Sarlahi I	ψ_2	-9.85 (-11.33, -8.60)	-9.51 (-10.61, -8.60)
	Female (γ_6)	-0.17 (-0.35, 0.01)	-0.17 (-0.35, 0.01)
	Age 4 to 7 months (γ_7)	0.40 (0.15, 0.64)	0.40 (0.15, 0.65)
	Age 8 to 12 months (γ_8)	0.11 (-0.15, 0.36)	0.11 (-0.15, 0.36)
	Age 13 to 24 months (γ_9)	-0.39 (-0.64, -0.15)	-0.40 (-0.64, -0.15)
	Age 25 to 36 months (γ_{10})	-1.06 (-1.34, -0.79)	-1.07 (-1.35, -0.79)
	δ_1	-1.16 (-1.57, -0.76)	-1.15 (-1.55, -0.74)
	δ_2	-0.09 (-0.62, 0.41)	-0.05 (-0.57, 0.45)
	δ_3	-2.1 (-2.70, -1.52)	-2.01 (-2.59, -1.44)
	δ_4	0.68 (0.09, 1.26)	0.77 (0.20, 1.33)
	δ_5	-3.09 (-3.89, -2.31)	-2.98 (-3.77, -2.21)
	δ_6	-1.05 (-1.92, -0.20)	-0.95 (-1.80, -0.13)
	δ_7	-1.74 (-2.64, -0.88)	-2.64 (-2.52, -0.81)
	δ_8	-3.34 (-4.60, -2.17)	-3.22 (-4.51, -2.10)
Sarlahi II	ψ_3	-11.78 (-13.41, -10.35)	-11.1- (-12.29, -10.03)
	Female (γ_{11})	-0.16 (-0.67, 0.33)	-0.16 (-0.68, 0.32)
	Age 4 to 7 months (γ_{12})	0.19 (-0.46, 0.85)	0.19 (-0.45, 0.83)
	Age 8 to 12 months (γ_{13})	0.10 (-0.48, 0.71)	0.11 (-0.52, 0.75)
	Age 13 to 24 months (γ_{14})	-0.11 (-0.67, 0.46)	-0.11 (-0.69, 0.47)
	δ_9	0.06 (-1.20, 1.26)	0.07 (-1.17, 1.27)
	δ_{10}	-3.13 (-5.44, -1.30)	-3.04 (-5.09, -1.25)
	δ_{11}	-1.63 (-3.67, 0.42)	-1.57 (-3.61, 0.43)
	δ_{12}	-0.05 (-2.27, 1.91)	-0.08 (-2.17, 1.92)
All	β_1	1.03 (-0.46, 3.08)	0.37 (0.02, 1.15)
	β_2	0.21 (-1.17, 1.37)	0.39 (0.03, 0.97)
	β_3	0.85 (-0.01, 1.80)	0.36 (0.03, 0.79)
	β_4	-0.05 (-0.73, 0.67)	0.13 (0.00, 0.41)
	β_5	-0.94 (-2.41, 0.16)	0.09 (0.00, 0.30)
	β_6	1.23 (-0.14, 3.28)	0.11 (0.00, 0.34)

β_7	-0.70 (-2.81, 0.59)	0.11 (0.00, 0.35)
β_8	-0.99 (-3.45, 0.94)	0.16 (0.00, 0.52)
σ_β	1.12 (0.35, 2.39)	0.34 (0.11, 0.77)
σ_ξ	1.25 (1.12, 1.38)	1.26 (1.13, 1.39)
σ_Γ	0.44 (0.28, 0.67)	0.44 (0.29, 0.67)
σ_Δ	1.73 (1.23, 2.33)	1.70 (1.20, 2.30)

Note: All parameters are fit in a single model; some parameters vary by study within the model and others are common across all studies in the model.

eTable 15: Odds ratios (95% Credible Intervals) for specific differences in exposure values.

Reference Concentration	Comparison Concentration	Odds Ratio (95% CI)
50	35	0.44 (0.11, 1.21)
	37.5	0.46 (0.13, 1.19)
	75	1.86 (1.06, 3.28)
	100	2.68 (1.53, 4.73)
	150	3.39 (1.89, 6.10)
	200	3.31 (1.86, 5.90)
	400	2.63 (1.49, 4.65)
100	35	0.16 (0.04, 0.56)
	37.5	0.17 (0.04, 0.56)
	50	0.37 (0.21, 0.65)
	75	0.69 (0.50, 0.92)
	150	1.26 (1.02, 1.62)
	200	1.23 (0.91, 1.70)
	400	0.98 (0.64, 1.50)
200	35	0.13 (0.03, 0.48)
	37.5	0.14 (0.03, 0.47)
	50	0.30 (0.17, 0.54)
	75	0.56 (0.34, 0.89)
	100	0.81 (0.59, 1.09)
	150	1.03 (0.86, 1.22)
	400	0.80 (0.60, 1.04)

eFigure 4: ALRI rates across time for the (a) Bhaktapur study and (b) the two phases of the Sarlahi study. The case-control design of the Bhaktapur means that only relative rates of cases are plotted for that study, while incidence rates are shown for the Sarlahi study. Lines represent smooth trends with pointwise 95% confidence intervals.

