1. QUIC model simulation theory

Quick Urban & Industrial Complex (QUIC) Dispersion Modeling System rapidly enables rapid and detailed modeling of flow field around buildings and apply this generated wind profile in a particle dispersion model. In the simulation, emissions from 250 sources are tracked simultaneously to quantify the pollution concentration in the selected region. The QUIC model stands out due to its ability to capture turbulence and the effect on pollution dispersion in the vicinity of buildings. The model also provides building-scale results that can show emission hot spots and concentrations and their interaction to eddies and current in the built environment. This is achieved by combining mathematical models QUIC-URB and QUIC-PLUME. QUIC-URB simulates the velocity wind filed with building obstacles and QUIC-PLUME is a Lagrangian random-walk particle dispersion model, which calculates pollution concentration distribution in the field, the theory of each model is described below:

QUIC – URB is a diagnostic wind solver that computes the flow of 3D wind fields around the buildings. The model is based on the algorithm first developed by Röckle et al. (Röckle, 1990). In this fast response urban wind model, the initial velocity fields (u_o,v_o,w_o) are determined based on empirical parameterizations such as upwind and downwind cavities, street canyons and recirculation zones. After assigning initial velocity, the wind field is adjusted to satisfy mass conservation equation(Singh et al., 2008; 礒部, 2013).

QUIC-URB algorithm considers empirical wind parameterizations, which is capable of simulating eddies introduced to the building wake, thus providing complex turbulent flow fields. The street canyon (SC) algorithm is applied for simulating flows in building wakes(Singh et al., 2008). SC assumes that canyon flow could be categorized to skimming and isolated flow. When buildings are widely spaced, the flow pattern is similar to flow around two isolated buildings, which is denoted as isolated regime. As the distance between the building reduces, the building downstream obstructs the wake produced by the upwind building until the initial flow starts skimming over the buildings and drives eddies in the cavity, thus produces a strong vortex between these two structures, this is defined as the skimming regime.

Skimming regime is applied when:

$$\frac{s}{H} < 1.25 + 0.15\frac{W}{H} \; when \frac{W}{H} < 2, or$$

$$\frac{S}{H} < 1.55 \; when \frac{W}{H} > 2$$

Isolated regime is applied when:

$$\frac{S}{H} > 1.25 + 0.15\frac{W}{H}$$

Where S is the building spacing, H is the building height and W is the building width.

The formulation for specification of the initial velocity field between the buildings is:

$$\frac{u_0}{U(H)} = -\frac{d}{0.5S}\left(\frac{S-d}{0.5S}\right)$$

$$\frac{w_0}{U(H)} = -\left|\frac{1}{2}\left(1-\frac{d}{0.5S}\right)\right|\left(1-\frac{S-d}{0.5S}\right)$$

Where d is the distance downwind from the upwind building, w is the vertical velocity component, U(H) is the wind velocity at the top of the upwind building.

The mean wind field at height(z) above the building is calculated based on:

$$u(z) = \frac{u_*}{k} ln\left(\frac{z}{z_0}\right)$$

Where, u_* = friction velocity, z_0 = aerodynamic roughness.

The QUIC-PLUME model is a Lagrangian random-walk model, wherein the movement of gases and aerosols are tracked as they disperse in the air. The model deploys mean wind fields produced by QUIC-URB model. The presence of buildings causes horizontal inhomogeneity of the flow. The model applies a non-local mixing formulation that better quantifies the building wakes and cavities in street canyon. The algorithm uses the mean motions from QUIC-URB output and computes the horizontal gradients in turbulence parameters using the Langevin random walk equations(Williams et al., 2004).

Lagrangian random-walk model describe dispersion of airborne contaminants by tracking the release of air parcels and moving them with instantaneous wind, which is the combination of mean wind and turbulent wind(Michael D. Williams, Michael J. Brown, 2005). The equation describes the parcel position are:

$$x = x_p + U\Delta t + \frac{u_p^{'} + u^{'}}{2}\Delta t,$$

$$y = y_p + V\Delta t + \frac{v_p^{'} + v^{'}}{2}\Delta t,$$

$$z = z_p + W\Delta t + \frac{w_p^{'} + w^{'}}{2}\Delta t,$$

Where x,y and z are longitudinal, lateral, and vertical position coordinates of the particle, U ,V , and W are the x, y, and z components of the mean wind, u ′ , v ′ , and w ′ are the turbulent components of the instantaneous wind, and Δt is the time step.

The fluctuating components of the wind are calculated from:

$$u'(t+\Delta t) = u'(t) + du,$$

$$v'(t+\Delta t) = v'(t) + dv,$$

$$w'(t+\Delta t) = w'(t) + dw,$$

The details of set of equations to derive du, dv and dw from Folker-Planck equations and well-mixed condition can be found in the QUIC-PLUME theory guide(Williams et al., 2004).The local coordinate system, the treatment of non-local mixing, and reflection are described. The pollution concentration in unit release is estimated by equation:

$$x_{i,j,k} = \sum \frac{Q\Delta t_c}{n_{tot} dx_b dy_b dz_b t_{ave}}$$

This is the sum of PM2.5 particles that are found in the sampling domain during the average time t_{ave}, n_{tot} is the total number of particles released, d_{xb}, d_{yb}, and d_{zb} are the dimensions of the sampling domain, and Δt_c is the particle time step.

All scenarios were simulated under similar meteorological and environmental conditions. The QUIC model is used to simulate local pollution concentrations from continuously released emission sources over the average cooking period. Concentration data in each receptor grid were then extracted and processed by MATLAB.

2. Validation of QUIC model (water channel experiment)

The building wake was reproduced using Lego™ built block in a re-circulating water channel with honeycomb baffles to create laminar flow fields. The water tank geometry is shown in S5, and the experiment setup schematic is demonstrated in S6. The channel has flow control capability to maintain constant velocity for creating steady state. Fluorescent dye was released from a tube on top of the upwind building to simulate the stack emission through chimney. Videos of the dye release are recorded and divided into sequential photos to visualize the flow field in the building wake and to quantify pollution dispersion proportional to dye concentration, which are averaged to quantify pollution concentrations under steady state flow. The mocked-building wake water tank experiment is based on the following theory:

For an incompressible Newtonian fluid, the mass conservation and Navier-Stokes(momentum) equations of motion can be expressed as:

$$\frac{\alpha \bar{u}_i}{\alpha x_i} = 0$$

$$\frac{\alpha u_i}{\alpha t} + u_j \frac{\alpha u_i}{\alpha x_j} = f_i - \frac{1}{\rho} \frac{\alpha p}{\alpha x_i} + \nu \frac{\alpha^2 u_i}{\alpha x_j \alpha x_j}$$

Now, the scaling parameter is introduced to non-dimensionalize the Navier-Stokes equations. The technique can reduce the number of free parameters.

scale	Dimensionless variable
Length L	x*=x/L
Flow velocity U	u*=u/U
Time L/U	t*=t/(L/U)
Pressure P	p*=P/(ρU^2)

$$\frac{\alpha u*}{\alpha t*}+u*\frac{\alpha u*}{\alpha x*}=-\frac{\alpha P*}{\alpha x*}+\frac{1}{Re}\frac{\alpha^2 u*}{\alpha x*^2}+\frac{1}{Fr^2}g$$

When the flow in the water channel is turbulent enough (Re>5000), the term $\overline{\frac{\alpha \bar{u}_i}{\alpha x_j}}$ is negligible and thus, the viscosity is neglected, this is fluid property; the Renolds stress and turbulent stress dominant the flow, which are flow property instead of fluid properties. Thus, the water can imitate the flow in the atmosphere environment under turbulent conditions.

A dimensionless length scale factor φL is defined as

$$\varphi L=\frac{[L]_{field}}{[L]_{lab}}$$

where L is the length scale.

The dimensionless time scale factor φT is defined as

$$\varphi L=\frac{[t]_{field}}{[t]_{lab}}=\frac{[\frac{L}{U}]_{field}}{[\frac{L}{U}]_{lab}}=\frac{[L]_{field}[U]_{field}}{[L]_{lab}\ [U]_{lab}}=\frac{\varphi L}{\varphi U}$$

where U is the velocity of ambient flow, φU is a velocity scale factor.

The ambient concentration C for well mixed contaminant can be expressed as:

$$C = \frac{Q \times t}{V}$$

Where Q is the source mass flow rate, mg/s, t is the travel time of the contaminant; V is the control volume.

The concentration scale factor is introduced as:

$$\varphi C = \frac{[C]_{field}}{[C]_{lab}} = \frac{[\frac{Q \times t}{V}]_{field}}{[\frac{Q \times t}{V}]_{lab}} = \frac{[\frac{Q \times t}{L^3}]_{field}}{[\frac{Q \times t}{L^3}]_{lab}} = \frac{[Q]_{field}\, \varphi C}{[Q]_{lab}\ \varphi L^3}$$

which can be rewritten as:

$$\varphi C = \frac{[C]_{field}}{[C]_{lab}} = \frac{[Q]_{field}\ [UL^2]_{lab}}{[Q]_{lab}\ [UL^2]_{field}}$$

The flow velocity in lab (Ulab) is 0.04 m/s. The height of the building Hlab is 10 cm. and distance between the buildings is 20 cm. The volumetric flow rate of releasing the dye is $3.3*10^{-6}$ m^3. The experiment was recorded by camera, and the image was post processed to get the relative concentration.

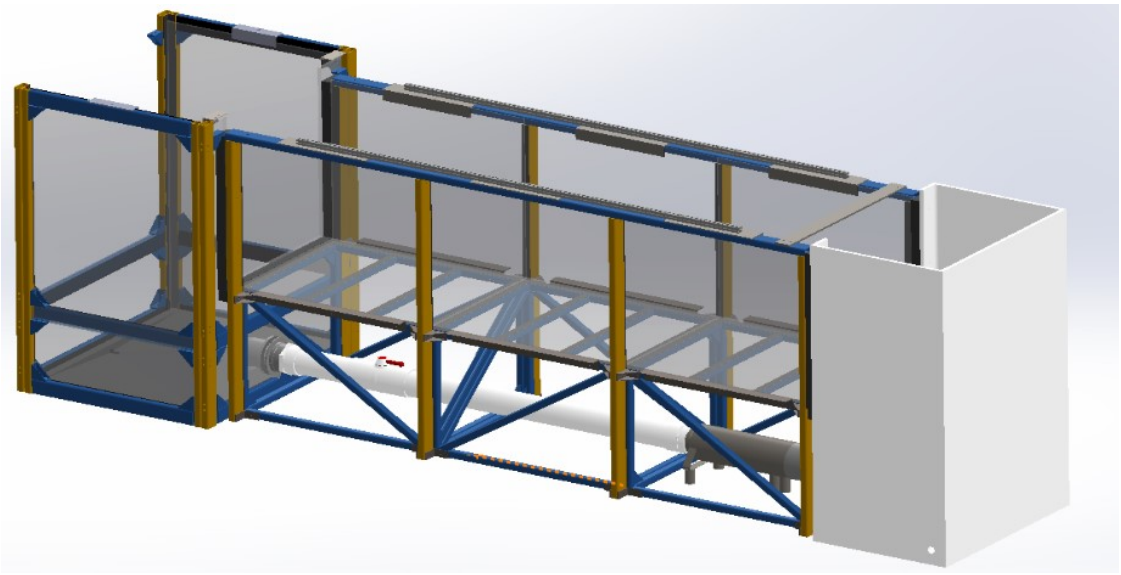

Figure S1. Water tank geometry

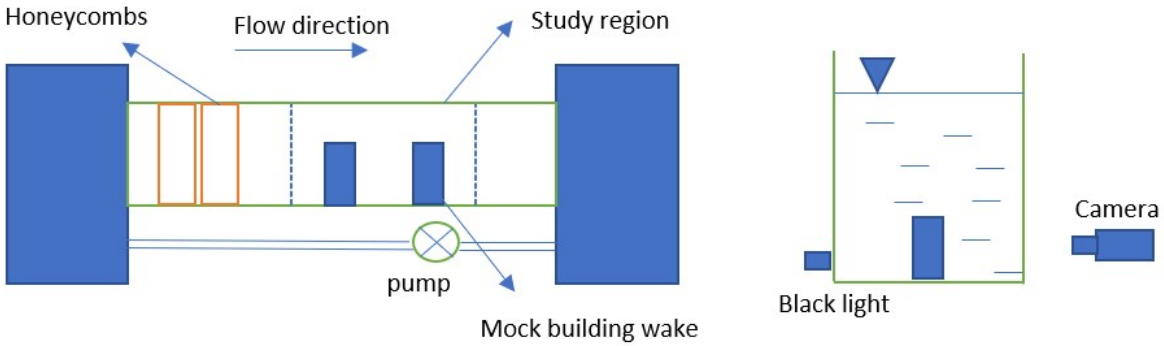

Figure S2. Experiment setup schematic

3. Geophysical information

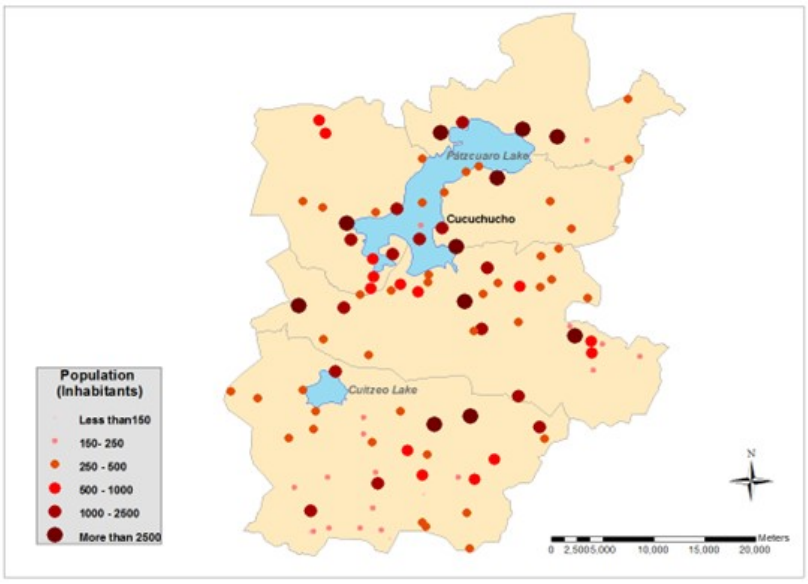

Figure S3. Local inhabitants' distribution near the selected region

a) b)

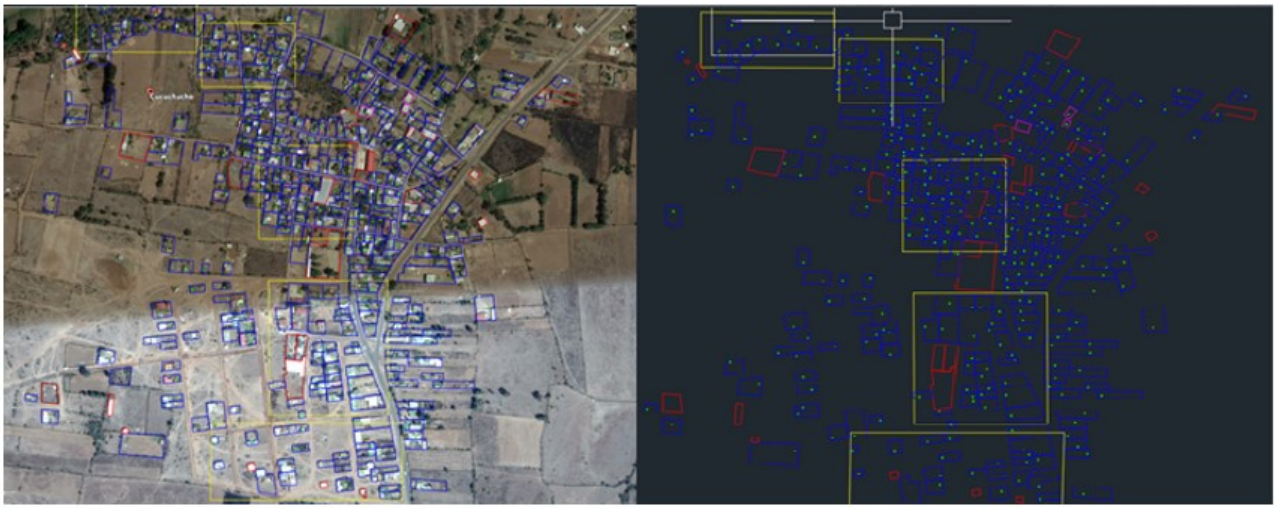

Figure S4. a) Distribution of households in the village

b) Distribution of emission sources on rooftop of households (represented by white dot)

4. Meteorology information

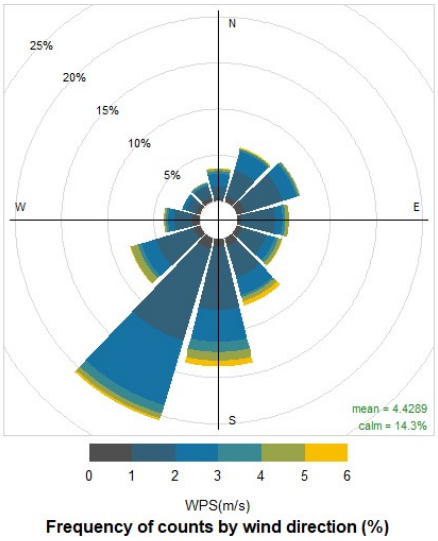

Figure S5. Wind rose for July-August near Cucuchucho

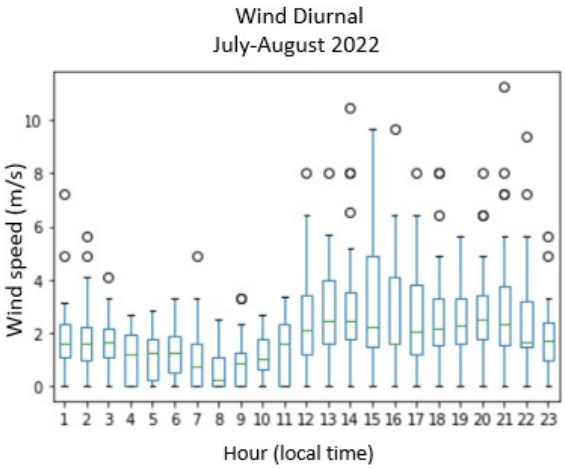

Figure S6. Wind diurnal for July-August

5. Stacking options

Table S1. Type of food items cooked with each stove that represent typical consumption patterns for this region

Cooking task	Stacking Option			
	Patsari-U-Type	**Patsari-LPG**	**LPG-U-Type**	**Patsari-LPG-U-Type**
1. Tortillas	Patsari	Patsari	U-Type	Patsari
2. Fired rice	Patsari	Patsari	U-Type	Patsari
3. Boil beans	U-Type	Patsari	U-Type	U-Type
4. Boil 1L of water	Patsari	LPG	LPG	LPG
5. Reheat	Patsari	LPG	LPG	LPG
6. Fried meals	Patsari	LPG	LPG	LPG

a) b) c)

Figure S7. Testing cook stove type

6. Pollution distribution in a street canyon

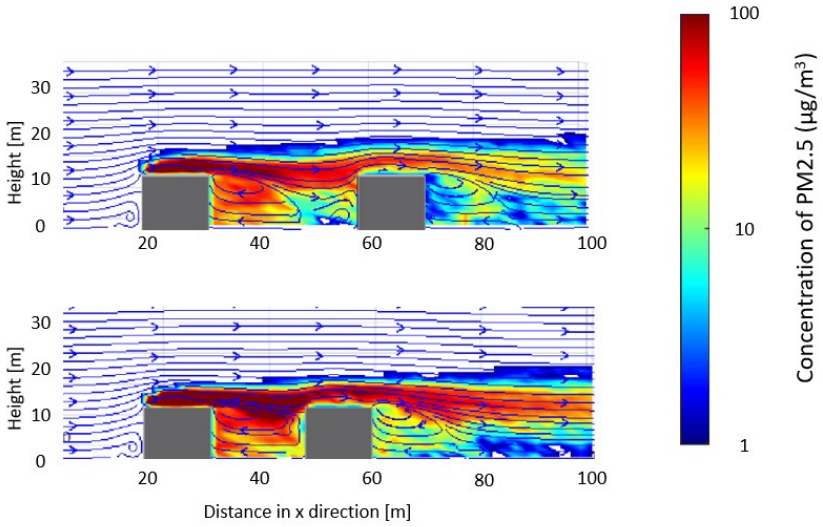

Figure S8. Pollution trapped in the building wakes under (a) interference flow (b) skimming flow

Street canyon serves as the basic geometric unit in urban or suburban regions. The configurations of a village are approximately repetitions of such street canyon units. The aspect ratio, H/W (H is the height of the building and W is the width between the two buildings) describes the street canyon features. The flow within a street canyon is determined by the building geometry, street orientation and wind conditions.

As indicated in figure S8, an eddy vortex develops at the building bottom at the windward face, and on the lee side, there is an eddy entering into the canyon. This is due to the low pressure caused by the flow separation from the sharp edges on building top and side. Pollutants accumulate with the backflow downwind of a building, indicating that this recirculation in the building wakes traps stove emissions for a longer duration. The presence of buildings leads to larger vertical mixing of the pollutants compared to flat terrain, thus contributing to the near-ground pollution concentration.

If the buildings are far apart, the flow pattern is identical to isolated buildings. When the distance between the building decrease, the windward side of the downwind building deflects eddies, and the upstream emission starts to affect the concentrations around the downwind buildings. This phenomenon is defined as wake interference flow ($2<W/H<4$) as figure S8 (a). As the building wake decreases further, the flow pattern turns to skimming flow ($W/H<2$) as figure S8(b) shows. Stable vortices are developed and thus the mixed pollutants are more influential to the downwind building front side. In addition, the pollutants are difficult to flush out and the particle residence time is longer since the bulk of the flow does not enter the canyon under this regime. This is one of the reasons the high-density region is more severely polluted.

7. Implications for indoor impacts

To estimate implications of each scenario on air available for infiltration into indoor environments average perimeter concentrations of $PM_{2.5}$ at 0.5m away from walls at the height of 1 m around the exterior walls of each house were computed, which reflects an estimation of air that infiltrates a home during cooking events. In general, average perimeter concentrations are higher than area concentrations due to the impacts of the building structure on pollution dispersion, combined with the lack of emission sources in agricultural areas. Figure S9 shows that perimeter $PM_{2.5}$ concentrations available for infiltration were higher than WHO interim target 1 for baseline, BAU and Scenario 1, but meet WHO guideline values for Scenarios 2,3,4.

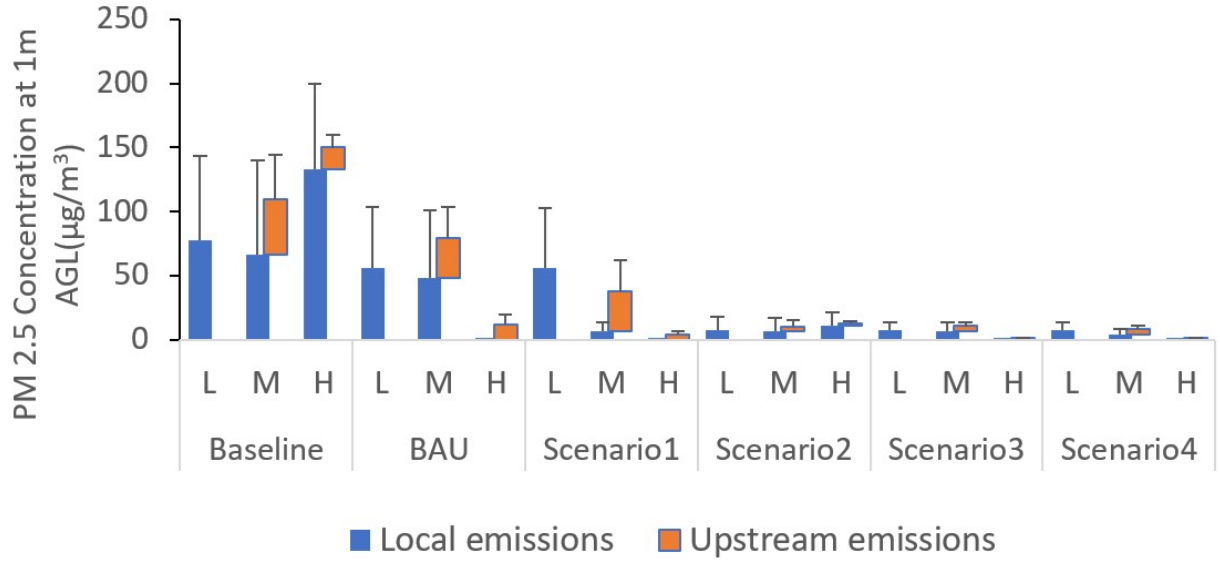

Figure S9. Perimeter averaged concentrations for each scenario and each packing density area (L: Low-packing density area; M: Medium-packing density area; H: High-packing density area)

	Baseline			BAU		
	L	M	H	L	M	H
Area	24.92±60.59	54.12±83.31	69.18±83.4	17.94±43.62	38.96±60	0.026±0.03
Perimeter	77.9±65.5	66.5±73.7	133±66.7	56.2±47.1	47.87±53	0.049±0.025
	Scenario 1			Scenario 2		
	L	M	H	L	M	H
Area	17.9±43.62	5.29±8	0.025±0.03	4.08±9.93	8.875±13.67	9.22±11.1
Perimeter	56±47	6.38±7.07	0.049±0.025	7.4±10.74	6.4±10.8	10.68±10.93
	Scenario 3			Scenario 4		
	L	M	H	L	M	H
Area	2.39±5.817	5.19±8	0.025±0.03	2.39±5.81	2.88±5	0.025±0.003
Perimeter	7.48±6.29	6.38±7.07	0.049±0.025	7.49±6.28	3.98±4.42	0.049±0.68

Table S2 presents the data table with area concentrations and perimeter concentrations for each scenario and fraction from upstream, and possibly fraction.

Figure S9 above represents an idealized scenario where all homes adopt the interventions. However, in practice, this is unlikely to occur. A more practical case is simulated in figure 10, which shows the impacts of 3 different adoption rate schemes in table S3 on average perimeter concentrations under scenario 4. Here it is assumed that people revert back to use traditional stove in combination with LPG. The figure demonstrates that even modest decreases in adoption have substantial impacts on neighborhood pollution concentrations measured at the perimeters of houses, which highlights the idea of transforming kitchens where the functional utility of the space is changed, rather than just switching stoves.

Packing density	Scenario A	Scenario B	Scenario C
High	LPG 80%; TSF LPG 20%	LPG 90%; TSF LPG 10%	LPG 100%; TSF LPF 0%
Medium	P+G 40%; TSF LPG 60%	P+G 60%; TSF LPG 40%	P+G 80%; TSF LPG 20%
Low	PK+LPG 40%; TSF LPG 60%	PK+LPG 60%; TSF LPG 40%	PK+LPG 80%; TSF LPG 20%

Table S3. Adoption rate schemes modeled in QUIC for Scenario 4

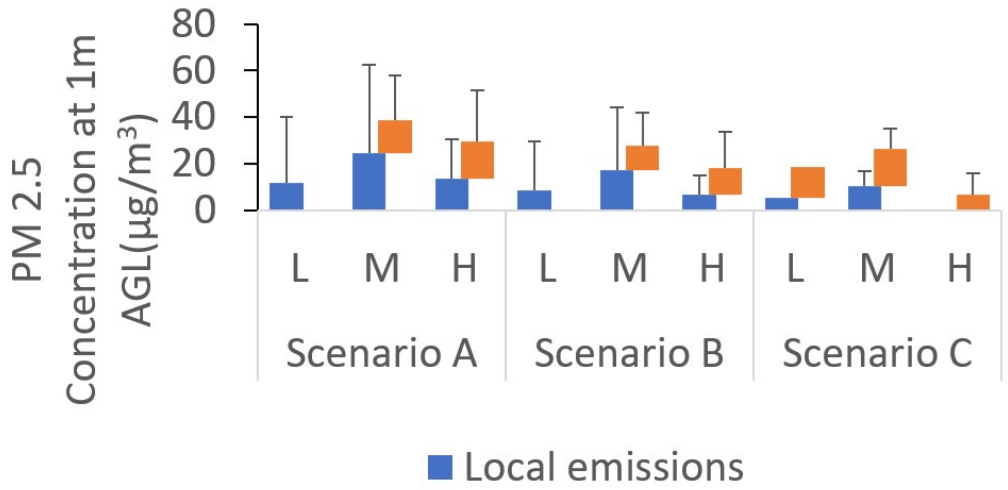

Figure S10. Averaged perimeter concentrations for scenario 4, assuming the adoption rates shown in table S3

(L: Low-packing density area; M: Medium-packing density area; H: High-packing density area)

8. Wind sensitivity analysis

The sensitivity of pollution concentrations to wind speed under different density factors is presented in figure S11, indicating that wind speed impact on the pollution concentration is independent of density factor.

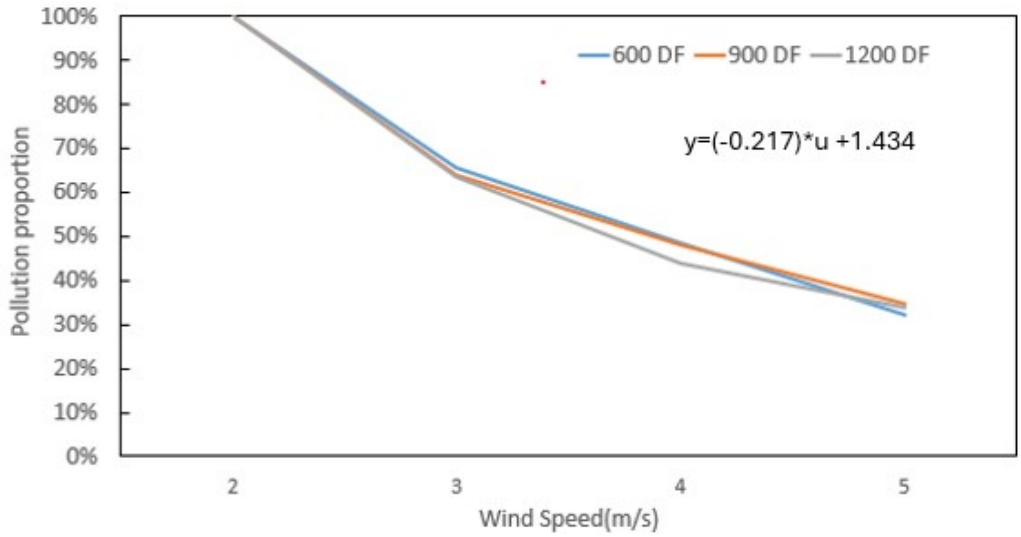

Figure S11. Pollution proportion under different wind speed

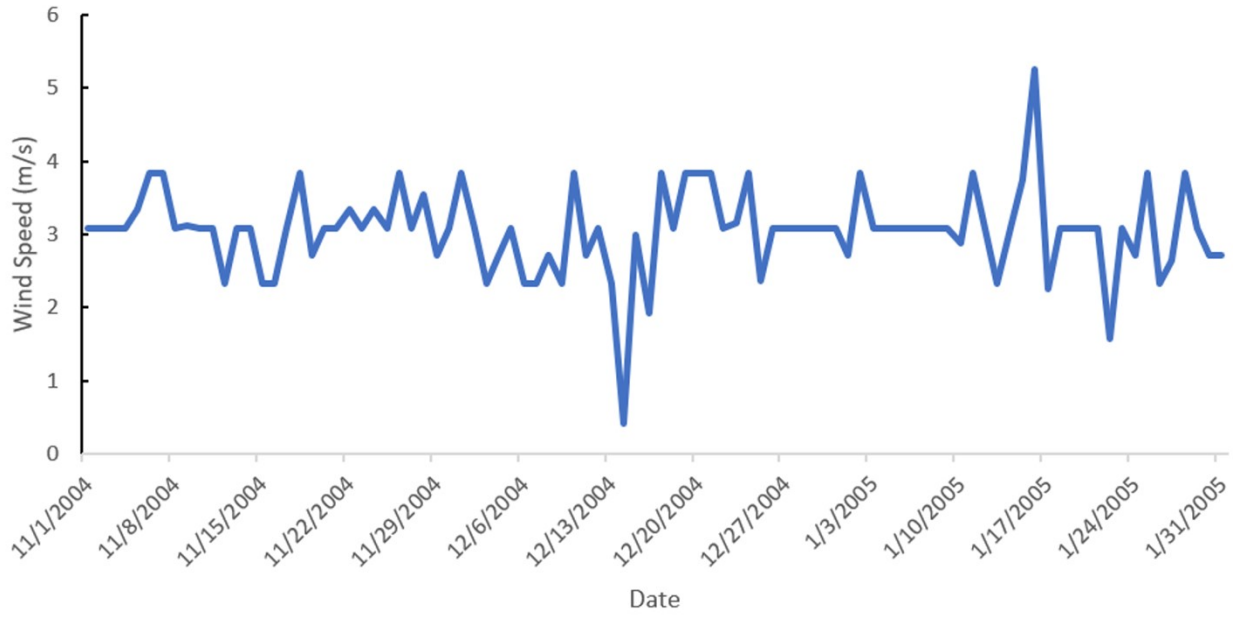

Figure S12. Wind speed during field measurement at village Comachuén

9. Chimney height sensitivity analysis

To check the sensitivity of pollution dispersion to the height of the chimney above the roof of the building (stack height) at which the pollutant is emitted. Figure S13 (a), (b) and (c) show the concentrations of pollution over the domain when the emission sources are placed at 0.5 m, 1.4 m and 2.2 m height above roof respectively. Increasing stack height shifts $PM_{2.5}$ concentrations further downstream and the region in which the pollution is trapped reduces. However, differences in the average domain concentrations and maximum concentrations due to varied stack heights were small. The majority simulations used a standard stack height of 0.5 m typical for the installation of chimney stoves in the region.

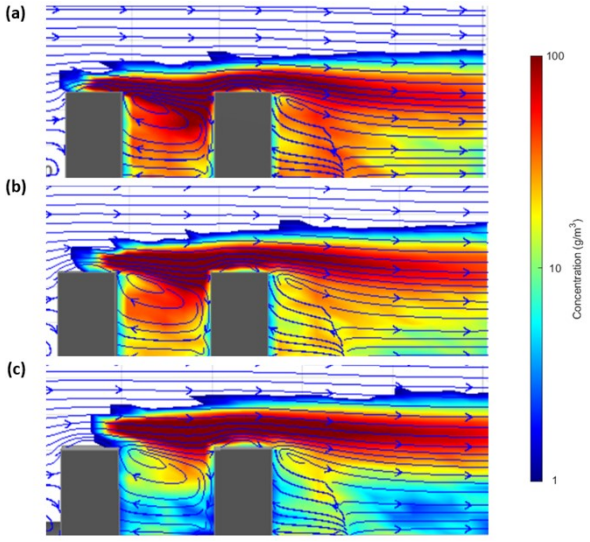

Figure S13. Pollution accumulation between building wake under different chimney height (a) 0.5m; (b) 1.4m; (c) 2.2m

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